MODELING MASS MOVEMENT TRANSPORT PROCESSES IN AN ALPINE ENVIRONMENT USING GRAPH THEORY: SAVAGE BASIN, CO, USA

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2019

Major Subject: Geology

ABSTRACT

Mass movement, which is a major geomorphic process in the San Juan Mountains of southwestern Colorado, plays a major role in landscape evolution of the mountain range. Alpine drainage basins are prime areas for sediment cascades, where debris is transported from cliffs in higher elevations to a variety of downslope storage landforms, or sinks, *via* various mass-movement processes, into stream channels in lower elevations, and exiting the basin. Distinct landforms are coupled and connected by geomorphic processes; thus, geomorphic coupling and connectivity are two important concepts for studying landforms and their functions in alpine basins. The study area is a glacial cirque known locally as Savage Basin. Unfortunately, no one has examined the sediment cascades in an alpine basin from source areas along mountain ridges, to stores in hillslopes, and eventually to sink areas along the basin floor. In this thesis, a mathematical method, graph theory, is applied to understand cascade pathways and landform linkages. A sediment-cascade simulation graph is constructed based on graph theory. Establishment of a landforms map for the study area is fundamental to constructing the graph and identifying sediment sources as well as pathways and transport processes. By mapping landforms and analyzing nodes and edges in the graph, I conclude that debris flows are the major mass movement process, and talus deposits provide most of the sediment supply to other landforms. The graph constructed in this thesis suggests that most landforms serve as contributing zones or intermediate zones for sediment cascades. Moraines serve as depositional zones, which receive sediment from surrounding landforms. The cascade graph also suggests that the sediment cascades in Savage Basin have a high geomorphic coupling efficiency and low connectivity. Landscape evolution of Savage Basin is explained in this thesis based on the

sediment cascades analysis and geomorphic history of the study area. The methodology and the application of graph theory in this thesis research provide a general theoretical framework for analysis of geomorphic processes and cascade systems for other basins in an alpine environment.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. John R. Giardino, who guide and support me in my Master's study, encourage me to keep research passion, and help me complete my thesis research. I am also grateful to the members of my committee for their patience and support in overcoming obstacles through my research.

I would like to thank my fellow graduate students and friends for their corporation, accompany and friendship, which helped me a lot during my Master's study.

Finally, I must express my deepest gratitude to my parents for supporting my study and my life goals unfailingly. My study and my thesis research in the U.S. would not have been completed without them.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. John R. Giardino and Dr. Hongbin Zhan of the Department of Geology and geophysics, Dr. Kevin Gamache of Water Management and Hydrological Science and Dr. Vatche Tchakerian of Department of Geography.

The field landform figures for Chapter 3 and the original 3-D Savage Basin terrain model image for Chapter 4 were provided by Dr. John R. Giardino.

All other work conducted for the thesis was completed by student independently.

Funding Sources

There are no outside funding contributors to acknowledge related to the research and compilation of this document.

NOMENCLATURE

G	Graph
V	Vertices
E	Edges
deg(v)	Degree of vertices
d (G)	Diameter of a graph
P_n	Path graph
C_n	Cycle graph
K_n	Complete graph
$K_{L,R}$	Complete bipartite graph
RF	Rock Falls
DF	Debris Flows
SA	Slush Avalanches

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CHAPTER I

INTRODUCTION

Introduction and Problem

The highest rates of erosion generally occur in the mountain ranges on Earth (Walling and Webb, 1996; Hinderer, 2001). Because of their high relief, steep slopes, extremes in temperatures, sparse vegetation cover, and seasonal precipitation amounts, considerable volumes of coarse and fine sediment are transferred from the upper regions of a drainage basin into the drainage network, and eventually out of the basin on an annual basis (Caine, 1974; Barsch and Caine, 1984; Owens and Slaymaker, 2004). Chorley and Kennedy (1971), Caine (1974) and Burt and Allison (2010) among others all suggest these mountain basins operate as cascading systems.

Chorley (1962) introduced the concept of general systems theory to geomorphology, which was followed by an expanded discussion by Chorley and Kennedy (1971) where they introduced a detailed systems' approach to physical geography and by extension to geomorphology. In their book, they introduced the concepts of morphological, cascading, process-response systems, and they defined a cascading system as:

"… one of the most important type of dynamic system and are defined as structures within which the output from one system forms the input for the next subsystem and within which a regulator may operate either to divert a part of the input of mass or energy into a store or to create a throughput producing the subsystem output." (Chorley and Kennedy, 1971, p. 77).

Sediment cascades are present in all alpine drainage basins. The sediment cascade consists of material from weathered cliff faces, then detached from the cliffs, transported downslope along various pathways *via* fluctuating geomorphic processes to a variety of basin stores such as, talus slopes, debris and avalanche cones, slope deposits, rock glaciers, floodplain deposits, and eventually into the various channels of the basin stream network (Giardino, 1979, 1980; Schrott *et al.,* 2002, 2003; Church, 2010). Heckmann and Schwanghart (2013) point out that many of these pathways do not result in direct connections of sediment from source areas into the channels of the network. Although the concepts of coupling and connectivity have well-established places in the geomorphic literature and are used interchangeably, several authors suggest they are rather distinct (Harvey, 2001; Faulkner, 2008; Heckmann and Schwanghart, 2013). They suggest that coupling should be used to describe the relationship between local-scale landforms whereas connectivity should be used to describe a system property on a scale of 10 km^2 and greater. Because I am interested in both the landforms and their functions they serve in an alpine drainage basin, I combine both terms and refer to the landform-cascade connections as coupled connectivity.

For my thesis research, I selected a large basin in the San Juan Mountain of Colorado. The San Juan Mountains are dominated by landforms produced by mass movement, glaciation, periglacial processes, and fluvial processes. Whereas uplift created the relief of the San Juan's, much of the landscape has been sculptured by glaciers and various forms of mass movement.

Mass movement, which is the downslope movement of rock and regolith near the surface of Earth is primarily the result of the force of gravity (Ritter *et al.,* 2002). Mass movement is one of the main geomorphological processes operational in the San Juan Mountains of southwestern Colorado (Blair, 2002). The San Juan Mountains are part of the Southern Rocky Mountains and area dominated by some of the highest and most jagged summits in the continental United States (Blair and Bracksieck, 2011). Mass movement is an important part of the erosional and transport cascade as the process moves materials from high to lower elevations. The common triggers of mass-movement processes include both human-induced triggers and natural triggers (Ritter *et al.,* 2002). And, this is very typical throughout the San Juan Mountains.

Mass movement in alpine basins in the San Juan Mountains plays a major role in landscape evolution of the various basins. The linkage of distinct landforms or landscape units by sediment transport is referred to as geomorphic coupling (Harvey, 2001). The sediment cascades are formed when the sediment sinks created by a geomorphic process are filled or depleted by other processes (Burt and Allison, 2010). And, the degree of coupling is connectivity.

Unfortunately, no one has examined the cascade of debris from the ridges surrounding these basins, to the stores, which are the various landform, to the stream channel, and out of the basin. I have studied the cascade of debris in Savage Basin.

Objectives

This thesis will analyze the debris cascade as it moves from the upper part of the drainage basin to its eventual exit *via* fluvial transport. Savage Basin in the San Juan Mountains serves as the study area for my thesis. One of my goals is to create a cascade transport model based on remote sensing imagery, field observations, graph theory, and digital elevation models, which help delineate sediment cascades and dominant processes.

The following objectives have been established for this thesis research:

- Identify the various sediment sources, pathways and processes;
- Use graph theory to identify cascade nodes and linkages; and
- Explain the landscape evolution of the Savage Basin.

CHAPTER II

METHODS

Graph theory is a mathematical tool to study points and lines by examining the ways in which sets of points are connected to each other by a series of lines. In graph theory, the points are referred to as nodes or vertices and the lines connecting the nodes are called edges. The use of graph theory to study problems in geomorphology gives a researcher the tool to examine the flow of mass and energy from one landform to another as well as how well the landforms are connected. The following section is a brief overview of the mathematical basis of graph theory. It is based on the very good book by Trudeau (1994).

Basic Concepts in Graph Theory

A graph $G = (V, E)$ includes a set of objects and relations between pairs of objects. For an edge in undirected graph: $e = \{u, v\}$, it represents e connects u and v, u and v are end points of e, u and e are incident, v and e are also incident, u and v are neighbors.

The degree of a vertex v, deg (v), is the number of edges incident to it, so the degree of a vertex is also the number of its neighbors. The degree of a graph is the maximum degree of its vertices. A vertex of degree 0 is called isolated.

A regular graph is a graph where each vertex has the same degree k, it is called k-regular. The complement of a graph G = (V, E) is $\bar{G} = (V, \bar{E})$. It has the same set of vertices, but for edges, two vertices are connected in $\bar{G}$ if and only if they are not connected in G.

For an edge in directed graph: $e = (u, v)$, it describes asymmetric relations, it represents the edge is has a direction from u to v. There are two types of degree for vertices in a directed graph, the indegree of a vertex v is the number of edges ending at v, the outdegree of a vertex v is the number of edges leaving v. Diameter of a graph, d (G), is the longest path between any two nodes in the graph (Urban and Keitt, 2001).

Paths, weighted paths and connectivity

A walk in a graph is a sequence of edges, such that each edge (except for the first one) starts with a vertex where the previous edge ended. The length of a walk is the number of edges in it. A path is a walk where all edges are distinct. A simple path is a walk where all vertices are distinct.

A cycle in a graph is a path whose first vertex is the same as the last one, all edges in a cycle are distinct. A simple cycle is a cycle where all vertices except for the first one is distinct. (And there first vertex is taken twice).

A graph is called connected if there is a path between every pair of its vertices. A connected component of a graph G is a maximal connected subgraph of G. For a connected undirected graph, the maximum number of edges is $(N^2\text{-}N)/2$, and the minimum number of edges is N-1 (Phillips, 2010).

A weighted graph associates a weight with every edge. The weight of a path is the sum of the weights of its edges. A shortest path between two vertices is a path of the minimum weight. The distance between two vertices is the length of a shortest path between them.

Basic graphs

There are some basic graphs, for example, path graph (P_n, $n \geq 2$) which consists of n vertices and n-1 edges, cycle graph (C_n, $n \geq 3$) which consists of n vertices and n edges, complete graph (clique) (K_n, $n \geq 2$) which contains n vertices and n(n-1)/2 edges.

A tree is a connected graph without cycles, which contains n vertices and n-1 edges. A graph is a tree if and only if there is a unique simple path between any pair of its vertices. A spanning tree of a graph G, is a subgraph of G, which is a tree and contains all vertices of G. A minimum spanning tree of a weighted graph is a spanning tree of the smallest weight.

A graph G is a bipartite graph when its vertices can be partitioned into two disjoint sets L and R. Every edge of G connects a vertex in L to a vertex in R, and no edge connects two vertices in the same part. A complete bipartite graph ($K_{L,R}$) means every vertices in L (or R) part connect every vertices in R (or L) part. For even n, C_n is bipartite, for odd n>2, C_n is not bipartite. A graph is bipartite if and only if it has no cycles of odd length.

A graph is called planar graph if it can be drawn in the plane such that its edges do not meet except at their end points. A face of a planar drawing of a graph is a region bounded by the edges of the graph, and there is always one infinitely large outer face. Euler's formula is used to identify if a graph is a planar graph or not.

Formula, theorem and algorithms in graph theory

Degree sum formula (Lemma) describes that for any graph G(V,E), the sum fo degrees of all its nodes is twice the number of edges:

$$\sum_{v \in V} \deg(v) = 2 \cdot |E|$$

In lower bound theorem, an undirected graph G (V, E) has at least |V| - |E| connected components. A graph is connected if any two of its nodes are connected. It a graph is connected, then |E| ≥ |V| - 1, if |E| = 0, then every node forms a connected component. It is obvious that the theorem is useless for graphs with |E| ≥ |V|.

A directed acyclic graph, DAG, is a directed graph without cycles. A topological ordering of a directed graph is an ordering of its vertices such that, for each edge (u, v), u comes before v. Such an ordering exists, if and only if the graph is acyclic. So every DAG has a topological ordering, and every DAG has a sink.

An Eulerian cycle (or path) visits every edge exactly once.it works for both directed and undirected graphs. A cycle must have the same starting and ending nodes, while in a path the starting and ending node should not necessarily be equal. There are two criteria: A connected undirected graph contains an Eulerian cycle (path), if and only if the degree of every node is even. A strongly connected directed graph contains an Eulerian cycle (path), if and only if, for every node, its in-degree is equal to its out-degree.

A Hamiltonian cycle visits every node of a graph exactly once, but there is no simple criteria or polynomial time algorithm for Hamiltonian cycle problem.

Kruskal's minimum spanning tree algorithm is a process which start with an empty graph T, and then add an edge of the smallest weight which does not create a cycle in T, it can repeat $n - 1$ times.

In Hall's theorem, in a bipartite graph $G = (L \cup R, E)$, there is a matching which covers all vertices from L if and only if for every subset of vertices S ⊆ L, |S| ≤ |N(S)|. |N(S)| means neighborhood vertices set of S.

In Euler's formula, if G is a connected planar graph drawn in the plane without edge intersections,

$$v - e + f = 2$$

Where v is the number of vertices, e is the number of edges and f is the number of faces in this drawing of G.

There are some numbers in graph theory that are used in theorem, such as chromatic number, clique number, independence number, Ramsey number and minimum vertex cover. In Mantel's theorem, if a graph on n vertices without triangles has at most $n^2/4$ edges. In Turán's theorem, if a graph G on n vertices contain no K_{r+1}, then it has at most $(1 - \frac{1}{r})\frac{n^2}{2}$ edges. In König's theorem, in a bipartite graph, the number of edges in a maximum matching equals the number of vertices in a minimum vertex cover.

Graph Theory Background

A graph contains a set of objects and relations between pairs of objects. A graph can be expressed as: vertices/nodes (V) in a graph, and edges (E) in a graph. A graph can be represented as an adjacency matrix, a square matrix with n^2 elements, in which n represents nodes, rows, and columns of non-zero nodes represent source and target nodes of edges. A graph can also be represented by an incidence matrix with m rows and n columns in which m is the number of edges in G, a node is non-zero if the node and the edge are incident (Phillips *et al.,* 2014).

Networks in graph theory, can be represented by n vertices 1, 2, …, n, source, and the destination vertices or nodes are fixed. Each edge can represent a flow, and if it is a weighted graph, the number on the edges can be the capacity of flow. For each vertices i and j (directed), integers capacities c[i,j] ≥ 0, and c[j,i] ≥ 0, c[i,i] = 0. For every two vertices i and j, flow f[i,j] is fixed, f[i,j] $\leq$ c[i,j], f[i,j] = - f[j,i]. Thus, total flow can be computed at the source A as $\sum_j f[A,j]$ or a destination B as $\sum_i f[i,B]$.

Graph theory has been applied in studying hydrology (Bunn *et al.,* 2000), fluvial channel network (Minor *et al.,* 2008, Brierley *et al.,* 2006), ecology (Urban, 1996, Cantwell *et al.,* 1993), climatology and seismology (Phillips *et al.,* 2014). Graph theory has also been used to study sediment transport in the Australian Alps by Heckmann and Schwanghart (2013). The components of a graph model may be objects (such as landforms, mass or energy storage compartments), processes (such as, weathering, fluvial erosion, and alluvial deposition), and phenomena or events, they are connected by fluxes of matter and energy, feedbacks, spatial or temporal sequencing or connectivity, and process-response relationships (Phillips, 2012).

Graph theory framework has been applied in ecology and biology to better analyze landscape connectivity and conservation planning in a visual way (Urban and Keitt, 2001, Minor and Urban, 2008). Urban and Keitt (2001) used habitat patches as nodes in a landscape graph and used edges, such as dispersal, to represent linkage of nodes, and they introduced some graph concepts such as clustering coefficient and compartmentalization in their study. They concluded that a minimum spanning tree graph can be applied in landscape connectivity analysis to evaluate the importance of different habitat patches in a landscape. Cantwell and Forman (1993) also used graph theory to construct ecology modeling and twenty-five landscape graphs based on aerial photographs, they produced three types of nodes and edges cluster to represent configurations of patches, corridors, and the matrix. Graph theory has been applied in analyzing two-dimensional fracture network by Ghaffari (2011), who mapped nodes in a graph as fractures, and created edges if two fractures intersected. Ghaffari (2011) used a network algorithm in fracture systems, and introduced a clustering coefficient, the degree distribution, geodesic distance (*e.g.,* the shortest path connecting any two nodes), average path length, and analysis of sub-graph in his study.

Geomorphic coupling and connectivity have critical implications for geomorphic dynamic systems (Heckmann *et al.,* 2013). They have been used as a major factor of sediment budgets in mass movement processes (Caine and Swanson, 1989; Harvey, 2001, 2002). Although debris budgets are important in analyzing mass movement processes, most research has focused on using geomorphic mapping to study sediment budgets but have not been used in quantitative and visual perspectives. Graph theory has been applied to analyze properties such as connectivity and coupling in sediment cascades spatial systems by several researchers whose study are discussed in following section.

Previous research in sediment cascades

Heckmann, Schwanghart and Phillips (2015) have reviewed research related to graph theory application in geomorphology, which include graph-model analysis of pathways, network structures, and system dynamics, and they conducted a hypothesis: “if geomorphic system properties and behavior depend on system structure and if graph theory is able to quantitatively describe the configuration of system components, then graph theory should provide us with tools to help in quantifying system properties and in inferring system behavior.” (Phillips *et al.,* 2014, pp. 131). The authors analyzed various examples in fields related to geomorphology, they discussed different system properties based on graph models, such as complexity, stability, sensitivity, and synchronization. They also reviewed graph applications in spatial explicit networks, which mainly refer to cascading systems.

Heckmann and Schwanghart (2013) analyzed sediment cascades and network structure in a central alpine catchment using graph theory combined with digital elevation models. Vertices or nodes in a graph were represented by DEM raster cells. And edges, which represent sediment trajectories, are produced between source and target cells of sediment pathways. The authors stressed the importance of mass movement and their interactions, and evaluated the modeling approach in their paper.

In a graph, the geomorphic coupling can be indicated by analyzing nodes with in-degree and out-degree. According to Heckmann and Schwanghart (2013), the sources are the nodes with 0 in-degree, and out-degree > 0, the sinks are nodes with 0 out-degree, and in-degree > 0. The in-neighborhood of each node represents the sediment-contributing area.

To construct a transport model, Heckmann (2013) used high resolution, process-based models in SAGA GIS to simulate potential sediment pathways for rockfall, debris flows, and channel network in his study area. Wichmann (2017) also conducted a gravitational process path (GPP) GIS-based model to simulate gravitational processes such as debris flows and rock falls. In the simulation model he determined different input parameters, such as slope threshold, divergence factor, persistence factor, free-fall threshold, mass-to-drag ratio, critical-flow velocity, and gliding friction, for rock falls, debris flows, slope wash, and fluvial bedload transport. He also applied various approaches in the simulation model such as, random walk approach, MFDF algorithm (multiple flow directions for debris flow), and one-parameter friction model. Then the author created transport models using graph theory to better understand geomorphic coupling in an alpine catchment. His transport model was constructed as an acyclic digraph with nodes and edgelists for different types of mass movement.

Connectivity is an important factor when studying networks in graph theory. Connectivity in mass movement processes relates to the degree of geomorphic coupling, this connectivity represents functional connectivity within a sediment cascade (Phillips *et al.,* 2014). In Heckmann and Schwanghart's study (2013), they contracted nodes in the graph, and conducted a summary graph model of sediment cascades, where weighted edges in the summary graph model represents path-length in each sediment cascade graph, and the paths in their study, which refer to sediment cascades in a graph, represent sequences of edges between source and sink nodes in the graph.

Methodology in This Thesis

The methodology was designed to accomplish the objectives of this thesis. My presentation is formatted with the specific objectives, so the methodology that will be used to achieve each objective is presented. The methodology for the whole thesis can be seen in Figure 2.1 and explained in detail under each objective.

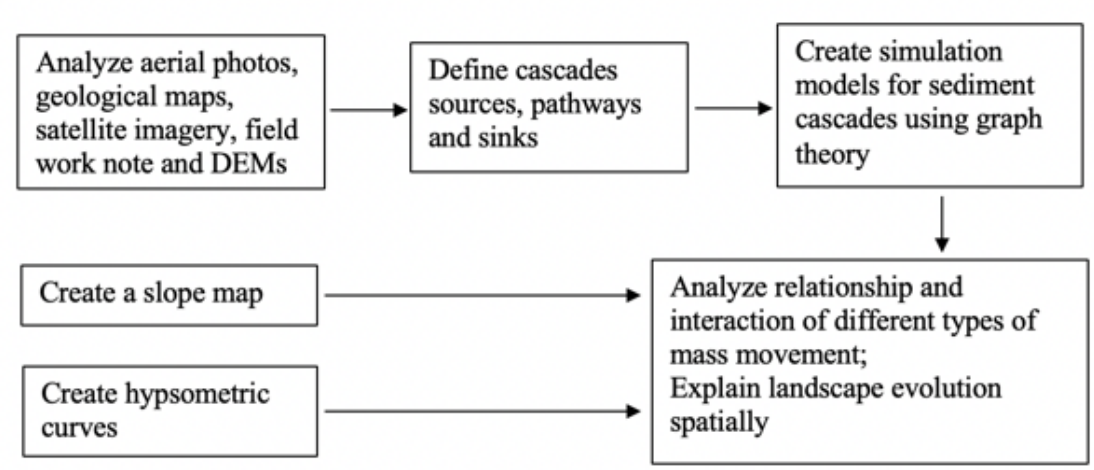

Figure 2.1. Diagram of thesis methodology.

Objective 1. Identify the various sources, pathways and processes

To identify various sources, pathways, and processes for sediment transport in Savage Basin, various methods, including satellite imagery, a digital elevation model, field observations, a geomorphic surficial deposits map, and a geologic map, are used in this thesis research. Different data sources are combined to analyze the sediment cascades characteristics in Savage Basin, a 3-D terrain model is produced to map the types of landforms in the study area. At the same time, the field observations, satellite imagery and the surficial deposits map are used to aid in identification of these landforms and to better understand the landforms and sediment transport processes from different perspectives. The sediment cascades in Savage Basin include the cliff faces, solifluction, rock falls, debris flows, debris avalanches, slush avalanches, talus, talus cones, moraines, slope wash deposits, and fluvial deposits. A map of these landforms is produced and overlay on a 3-D terrain model of Savage Basin using Adobe Photoshop. This 3-D image provides a clear view of all landforms and their potential connections and links in the study area. A slope map and a hypsometric curve are created based on digital elevation model in ArcMap®. The hypsometric curve shown the relationship between surface area and elevation of the basin.

Objective 2. Use graph theory to identify cascade nodes and linkages

To analyze the debris cascades and sediment transport characteristics, I use graph theory to explore the sediment sources, pathways, and sinks in this alpine basin. The simulation models of various landforms in Savage Basin are produced and can be viewed as a graph, which are helpful in analyzing and predicting the debris cascade and its evolution in the alpine basin from a spatial perspective. I also use graph theory to establish the relationships and interactions of the different types of mass movement in the study area and to quantitatively identify the dominant processes.

A directed graph constructed in this thesis research serves as a theoretic frame work for the various types of geomorphic processes in Savage Basin. The graph contains nodes and edges, which represent landform types and the linkages between any pair of nodes, respectively. Source nodes and sink nodes can be identified in the contribution/initiation zone and the deposition zone, respectively based on landform mapping on a 3-D terrain model of Savage Basin. The degree of nodes represents the geomorphic coupling of different landforms in the basin, and the weighted edges represent the connectivity level of different types of landforms. The weighted edges in the graph represent path length of any pair of nodes (*i.e.,* landforms). A path is a sequence of edges, such that each edge (except for the first one) starts with a vertex where the previous edge ended. The length of a path is the number of edges (*e.g.,* linkage of different landforms) in it.

From a simulation model based on graph theory, we can explain the sediment transport pattern in Savage Basin directly through a graph view. Geomorphic coupling can be explained by nodes degree, interactions of sediment cascades can be analyzed by paths in the graph, and connectivity, which refers to degree of coupling, can be analyzed by path length and weighted edges.

Objective 3. Explain the landscape evolution of the Savage Basin

Modeling for sediment transport processes based on graph theory is applied in this thesis research to simulate various types of debris cascades in Savage Basin. The interpretation of the transport model, including the dominant processes in this alpine basin, the potential pathways of sediment, and the coupling pattern of various geomorphic processes, can be established by constructing the graph of the study area and analyzing the nodes and edges in the graph.

CHAPTER III

STUDY AREA DESCRIPTION

Introduction

The San Juan Mountains extended from Powderhorn on the north to Dobra on the west, Del Norte and Monte Vista on the east and the Colorado-New Mexico Border on the south. The San Juan Mountains do extend into New Mexico.

This study focuses on one alpine basin, Savage Basin in the San Juan Mountains (figure 3.1). The San Juan Mountains cover ~ 44,194 km^2 (17,063 mi^2). Elevation ranges from a high of 4,361 m (14,316 feet) at Uncompahgre Peak to a low of ~2,027 m (6,650 feet) at Durango. The east-west extent of the San Juan Mountains is 267 km (166 mi), and the north-south extent is 305 km (190 mi).

Savage Basin (37° 57′ 02″ N to 37° 55′ 27″ N by 107° 43′ 55″ W to 107° 46′ 24″ W) has a vertical relief of 1,035 m (figure 3.2), stretching from the lowest point of the basin at 3,042 m (9,981 feet) to 4,077 m (13,377 feet) at the highest point on the ridge surrounding the basin (figure 3.3). Savage basin covers an area of ~ 5.12 km^2 (1.98 mi^2).

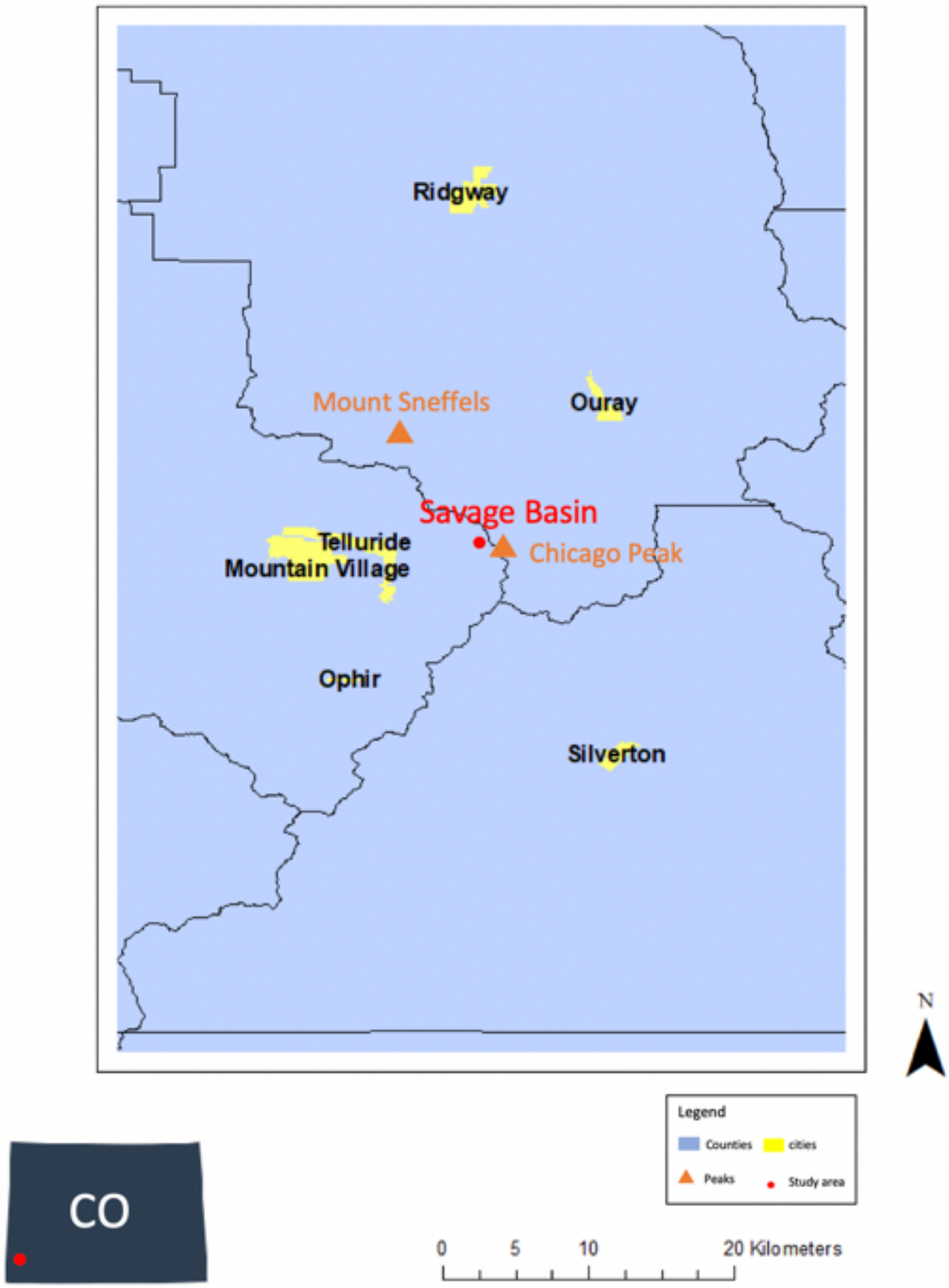

Figure 3.1. Location of study area.

Figure 3.2. Map of Savage Basin.

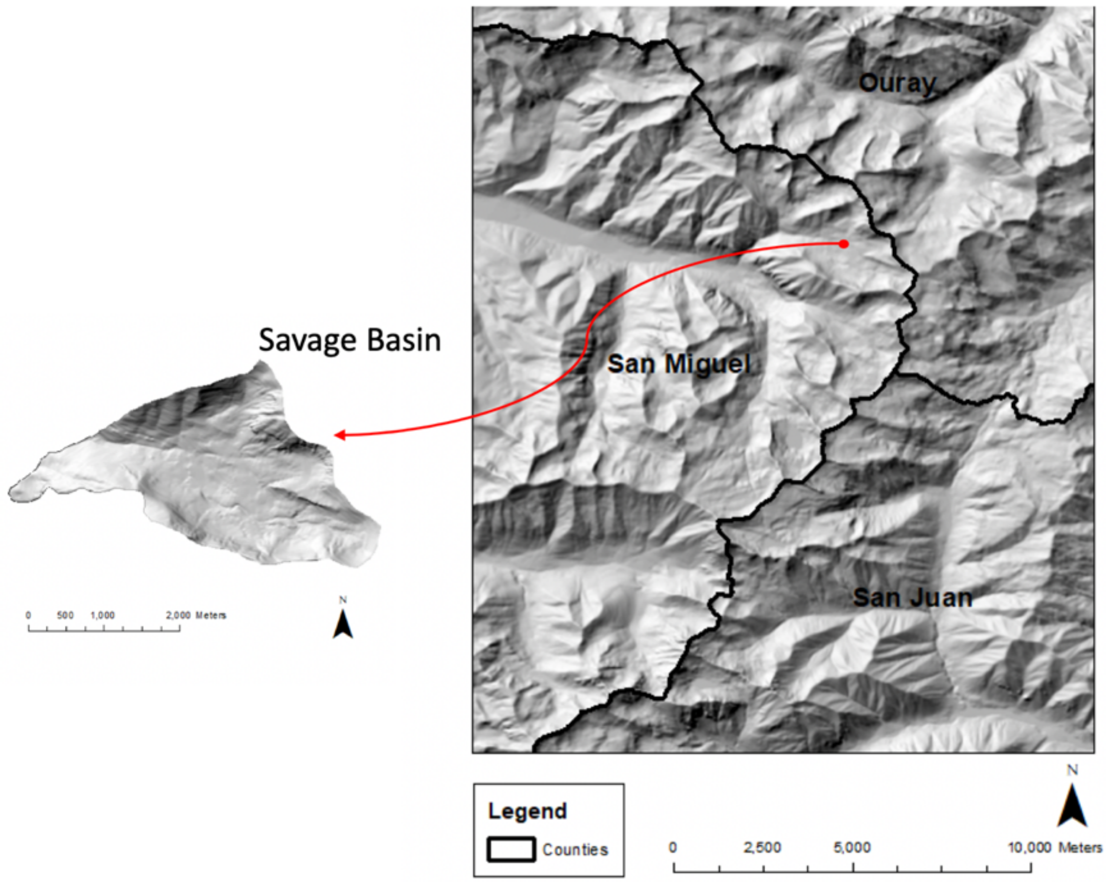

Figure 3.3. Reginal setting (right part, hillshade of 1/3 arc-second DEM) and detailed map (left part, hillshade of 1/3 arc-second DEM) of study area.

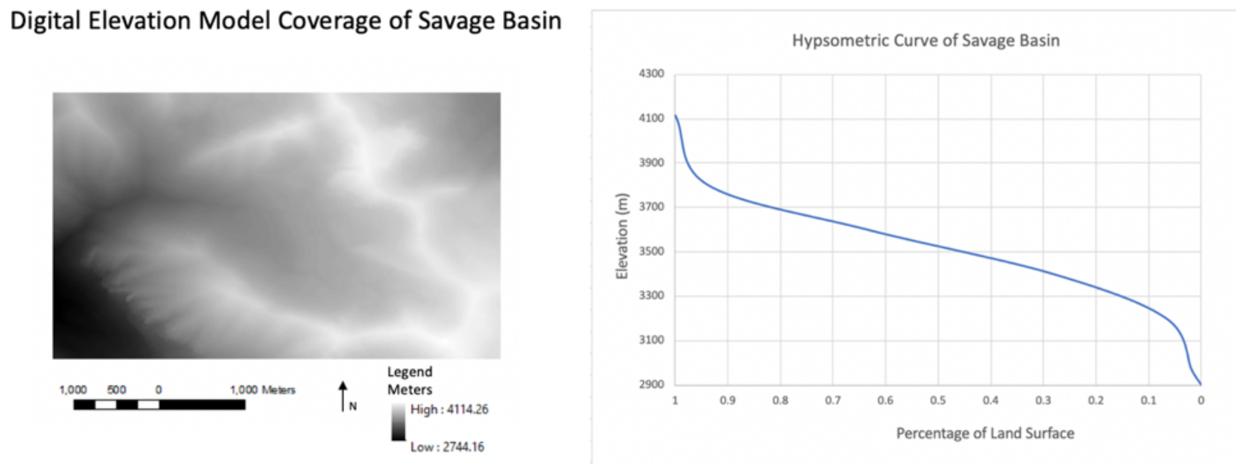

Figure 3.4. Terrain map of Savage Basin.

Geology

During the past 1.8 billion years, the San Juan Mountains have undergone a complex geologic history ranging from tectonic uplift to volcanic activity, glaciation, mass movement and fluvial activity (Blair, 2002 and Bracksieck, 2011). The geology of the basin is shown on the DEM in figure 3.4 and figure 3.5. The oldest rocks, which are Precambrian gneisses and schists, area mostly exposed in the Needle Mountains (Howe, 1995), and represent the oldest mountain-building events (Blair, 2002 and Bracksieck, 2011). Overall the San Juan Mountains consist mainly of Tertiary volcanic rocks, which overlie Paleozoic rocks with younger sediments resting unconformably upon pre-Cambrian formations (Howe, 1995).

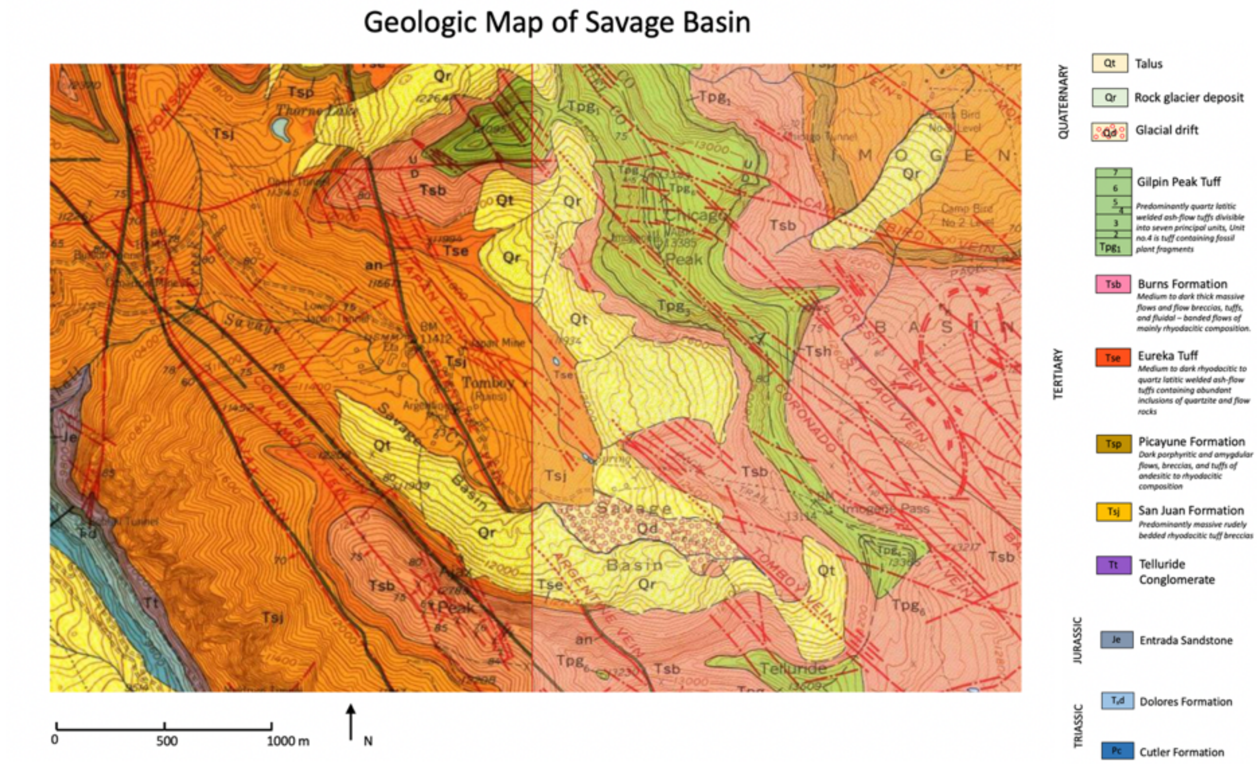

Figure 3.5. Geologic map of Savage Basin.

Geologic map with satellite image: Savage Basin outline

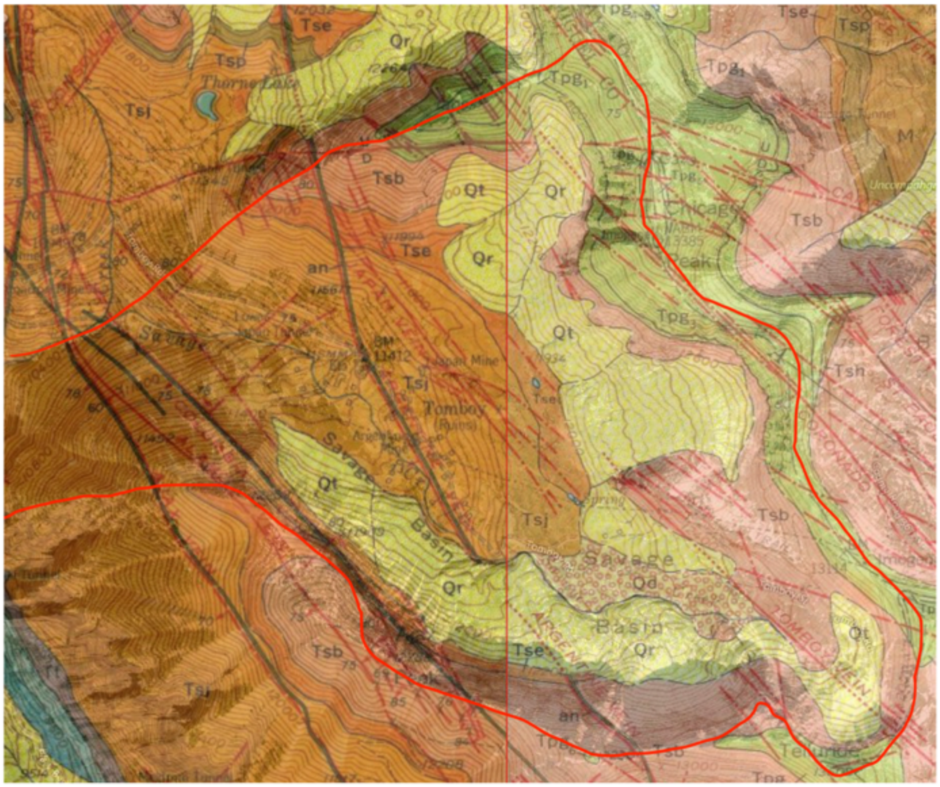

Figure 3.6. Geologic map and satellite image of Savage Basin.

Although the San Juan Mountains consist mainly of volcanic rocks, sedimentary rocks are present throughout the area. Stratigraphy is the area can be characterized as Cambrian quartzites, followed by Devonian and lower Carboniferous shales, limestones and sandstones. A series of shales, limestones, and sandstones of Triassic and Jurassic ages are characteristically reddish conglomerates, sandstones and thin limestones. Sources of the sedimentary rock are from the interior lowlands and seaways (Blair, 2002). Cretaceous sediments occur along floodplains and make up many of the mountain slopes; all sitting above the Eocene deposits. Considerable amounts of volcanic deposits occur in the central part of the mountains where the volcanic rocks rest upon the sedimentary formations. These deposits include rhyolite, andesite and basalt

(Howe, 1995). In early Tertiary a stable tectonic activity was recorded, volcanism occurred in mid to late Tertiary covering the area with rhyolites, ash-flow tuff and volcanic breccias. Multiple glaciations occurred and post-glacial processes shaped the landscapes, glacial deposits are in the San Juan Mountains are formed in Pleistocene and alluvial deposits are formed in Holocene age (Blair *et al.,* 1996).

Geomorphology

In the San Juan Mountains, Cenozoic tectonics and volcanism followed by Quaternary glaciation have created a rugged alpine landscape (Fitzgerald, 1994). The landscape of the San Juan Mountains has been shaped by various processes including orogenic uplift, volcanism, glacial, fluvial, and mass movement processes. In addition, human have played a major role in altering the surface in the San Juan Mountain through mining and their urbanization (Gamache *et al.,* 2018). According to Blair (2002), volcanism dominated the San Juan Mountains formation from Oligocene through Miocene, whereas uplift occurred from late Miocene to Pliocene (Blair, 2002 and Bracksieck, 2011).

Glacial, fluvial, and mass movement processes played an important role in the present-day look of the San Juan Mountains. Various landforms including cirques, moraines, U-shaped valleys, valley-train deposits, landslides, debris flows, avalanches, floodplains, step-pools and V-shaped valleys occur throughout the San Juan Mountains (Kelkar and Giardino, 2016). The transport of unconsolidated debris plays a major role in influencing and modifying not only the geomorphic features but also the overall landscapes in the San Juan Mountains.

Savage Basin, which serves as study area in this thesis, contains various types of landforms. These landforms include: cliffs, slopes, rock glaciers, talus, moraine deposits, slope wash deposits, fluvial deposits, talus cones and avalanche cones. Solifluction is a special kind of creep process in cold climates, it is accelerated by frost processes in tundra associated with saturated ground, often above a permafrost layer (Ritter *et al.,* 2011). Rock fall involves a single mass that travels as a freely falling body with little interaction with other features, it occurs where parent bed rock is well jointed and a steep slope is developed on the rock face. Debris flows (figure 3.7 and figure 3.8) are a complex group of gravity-induced rapid mass movement types that are categorized between landslides and flood deposits (Johnson, 1970), debris flows, various grain sizes from boulder to clay.

Figure 3.7. Debris flows.

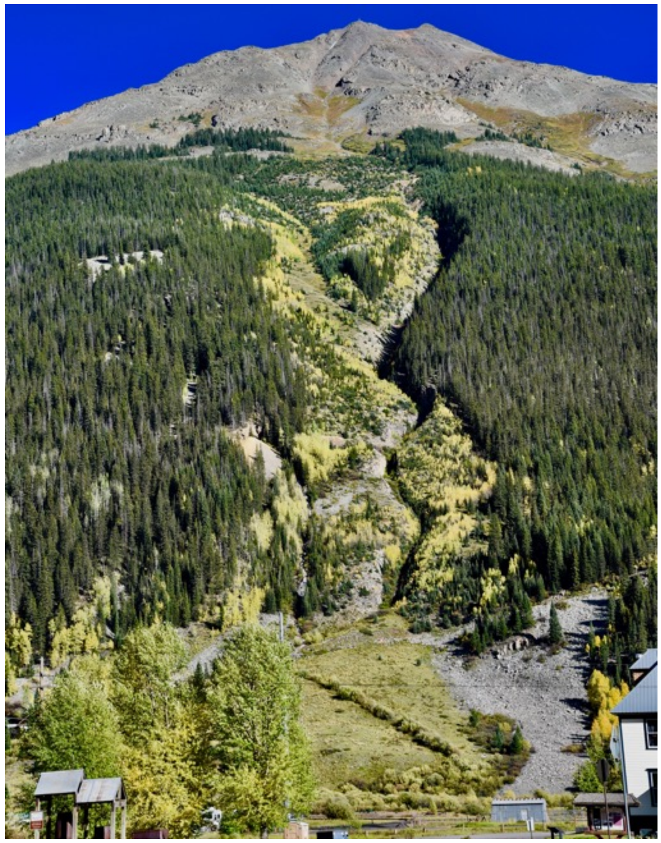

Figure 3.8. An avalanche track.

The prerequisite of debris flows includes an abundant volume of water, an abundant amount of fine-size sediment, and a steep slope (Costa 1984). Flow permits a long distance of mass transport, and it is helpful to explain the distribution of source rock within the deposits (Ritter *et al.,* 2011). Avalanches are a rapid moment of snow and debris, which is generated on steep bedrock slopes with thin colluvial and soil cover. Slush avalanches are a form of avalanches, which usually occurs in late spring and a result of saturation of the snowpack. Talus (figure 3.9 and figure 3.10) is formed when materials eroded from a cliff face by rock fall accumulates below the cliff in the profile, the maximum angle talus can obtain before failure is its angle of repose of ~ 34°.

Figure 3.9. A new talus cone just developed.

Figure 3.10. A talus cone.

Rock glaciers (figure 3.11) are large, tongue-shaped or lobate feature composed of angular boulders, they link frost weathering, rock fall, and avalanche processes to debris transport in. mountain regions (Janke and Fraunfelder 2008).

Figure 3.11. Rock glacier.

Moraines are a depositional feature and is constructed by accumulation of drift (Flint 1971). In this thesis moraines in Savage Basin refers to ground moraine. Slope wash deposits contain soil and rock material which is transported down a slope by mass movement processes (Bates and Jackson, 1987). River channels is developed because master rills carry more water and erode faster, then the master rills create new slopes directly toward center. Channel patterns include straight channel, meandering channel, braided channel and anastomosing channel. Small floodplain deposits also occur in Savage Basin, fluvial deposits are sediment that are transported and deposited by rivers in a continental environment (Slatt, 2006).

Climate

According to NOAA climate data (NOAA 2018), the average temperature range is from 1.3˚C (34.3˚F) to 14.9˚C (58.8˚F) based on the climate data from September 2015 to September 2018 for one climate station in Ouray. The average annual rainfall is 596.31 mm (23.48 inches) based on the climate data from 2007 to 2017 for two stations in Ouray, and the average annual snowfall is 3892.23 mm (153.24 inches) based on the climate data from 2007 to 2017 also for two stations in Ouray. According to U.S. Climate Data, the annual temperature range is from 1.3˚ C (22.0˚F) to 14.9˚C (53.6˚F) in Telluride. The average annual rainfall is 596.31 mm (23.38 inches), and the average annual snowfall is 3892.23 mm (175 inches) in Telluride. Figure 3.12 shows the annual temperature and precipitation for Telluride.

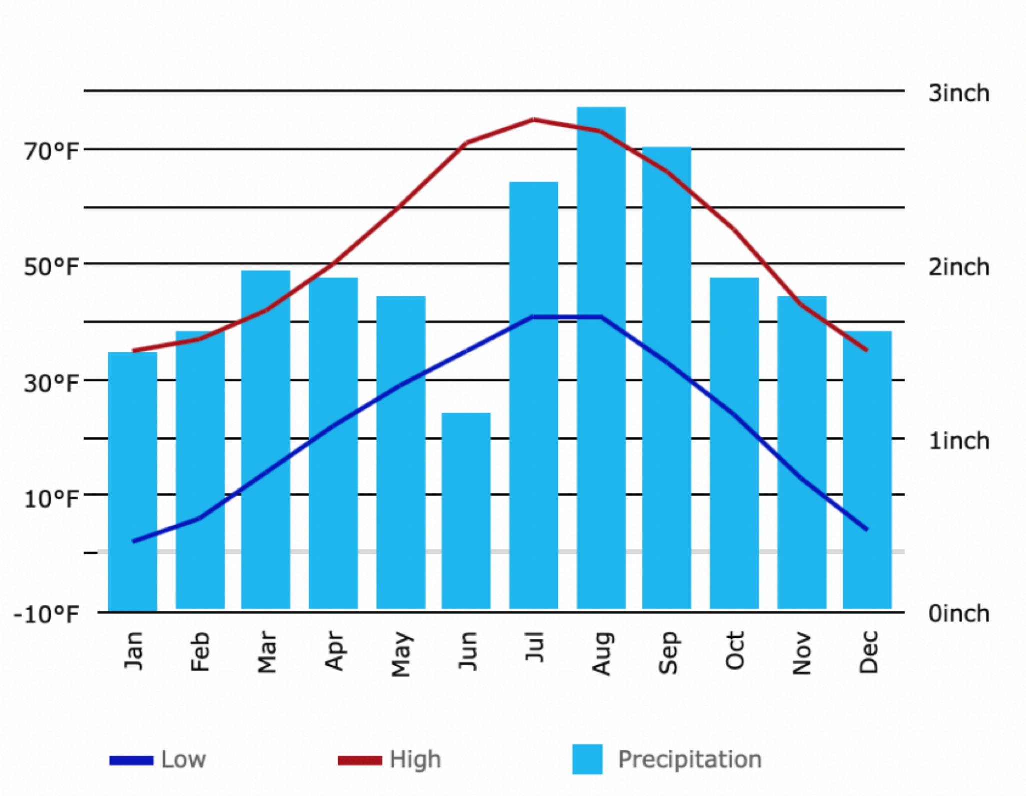

Figure 3.12. Annual temperature and precipitation for Telluride (U.S. climate data, 2019).

Vegetation

The basic vegetation types in the San Juan Mountains include piñon-juniper woodlands, ponderosa pine (Pinus ponderosa), Aspen (populus tremuloides), mixed-conifer (Pinophyta), warm-dry mixed-conifer (Pinophyta), cool-moist mixed-conifer (Pinophyta), spruce-fir and cold-wet mixed-conifer (Pinophyta) (Blair and Bracksieck, 2011). Insects can survive in an alpine and arctic environment and bear cold temperature and low water availability. Drought is one of the most important factors causing pest outbreaks (Blair and Bracksieck, 2011). Bark beetle outbreaks, mainly include pine beetle and spruce beetle, in southern Colorado have killed millions of acres of pine trees and spruce-fir trees (Woodward *et al.,* 2018), which may result in potential wildfires in the San Juan Forests.

Road Access

The study area can be accessed *via* U.S. Highways 550, 145 and Country roads 648, 62 and 26A. Access to the field site is gained by four-wheel drive road from Telluride or over Imogene Pass from Ouray and by hiking trails.

CHAPTER IV

DISCCUSION

Results and Interpretation

This thesis research used 3-D terrain model image, satellite imagery, and numerical modeling to simulate sediment cascades in Savage Basin. Different landforms in Savage Basin were mapped on a 3-D terrain model to illustrate sources, pathways of sediment and transport processes by mapping landforms and their processes for Savage Basin.

To simulate sediment transport processes in Savage Basin, a graph was constructed and analyzed quantitively based on graph theory. Nodes in the graph were created to represent different types of landforms in the study area, which includes cliffs, talus and talus cones, rock glaciers, moraines, and fluvial deposits. Edges were produced in the graph between source and sink nodes to represent a sediment pathway. Different sediment cascades system properties, such as geomorphic coupling and connectivity, were analyzed. Based on the graph model, slope map and hypsometric cure of Savage Basin, an explanation for mass movement characteristics and landscape evolution patterns is suggested.

Five different landforms including cliffs, talus and talus cones, rock glaciers, moraines, slope wash deposits, and fluvial deposits were mapped in Savage Basin. The lower part of Savage Basin has been modified by mining, and some landforms near Savage Creek have been destroyed by human activity. Five types of mass movement were also mapped in Savage Basin, which include rock falls, debris flows and debris avalanches, rock glaciers, slush avalanches, and solifluction.

In the construction of the graph, 295 nodes and 303 edges were created based on all the landforms and their linkages in Savage Basin. Dominant landforms and processes can be identified using this graph model, geomorphic coupling and connectivity were analyzed by interpreting nodes and edges in the graph as well as on some sub-graphs. A summary graph with a weighted edge represents path length of the sediment cascade/trajectory in the study area, and nodes in graph can be separated into three parts, contributing zone, hillslope processes, and deposition zone. Analysis and explanation of each graph are discussed in this chapter.

Mapping of sediment sources, pathways and processes

Landforms and movement processes were mapped on a 3-D terrain image (figure 4.1).

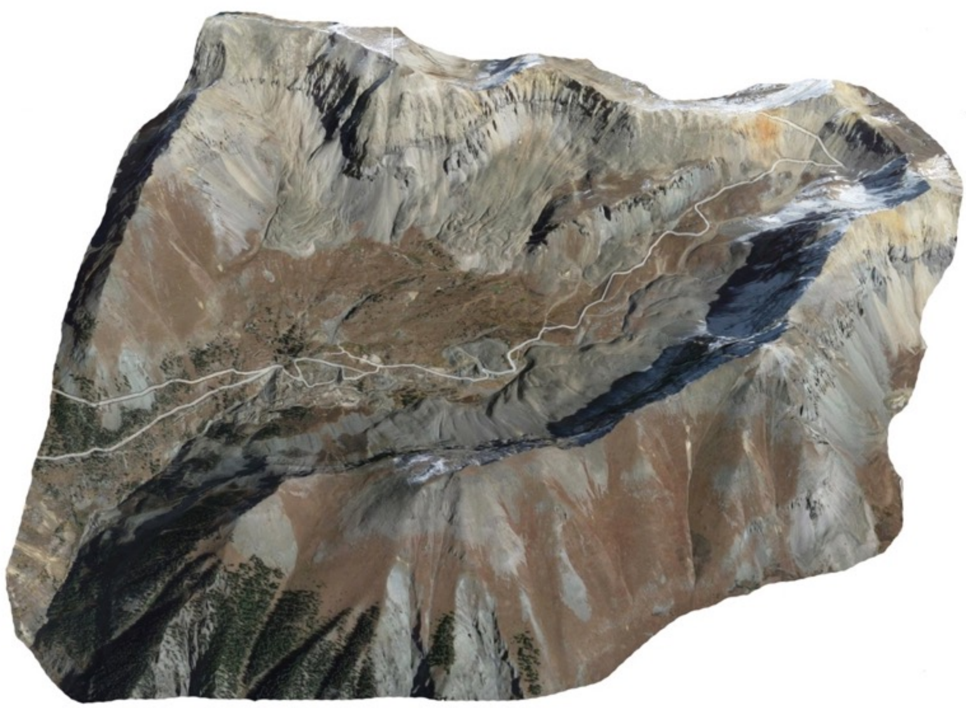

Figure 4.1. A 3-D image of Savage Basin.

To identify landforms and sediment pathways, different methods were combined including satellite imagery, aerial photographs, surficial deposits map, field observations and a digital elevation model.

I conducted an inventory of the storage capacity and locations of production and storage sinks in the basin to gage the coupling state of the sediment cascades and to appraise the sediment connectivity in Savage Basin. I visually identified and manually created a landform map of the basin beginning along the crest of the ridge surrounding the basin and continuing to and following the stream channel to its exit from the basin. Figure 4.2 shows the mapping results.

The individual landforms are elevational transitions of process driven cascades. I mapped these as sediment cascade based on how the sediment is routed from one store to lower store and I examined these coupling relationships based on Lexartza and Wainwright (2009) definitions that the physical contact of two neighboring sediment storages is a structural contact and that active transport of sediment across the contact between landform units is a functional contact if material was transferred as input or output. In the case of sediment between stores I mapped the boundary as coupled. In locations where there was no visual sediment transfer or a physical buffer exists as a cliff or larger extent of exposed bedrock, I mapped these as decoupled.

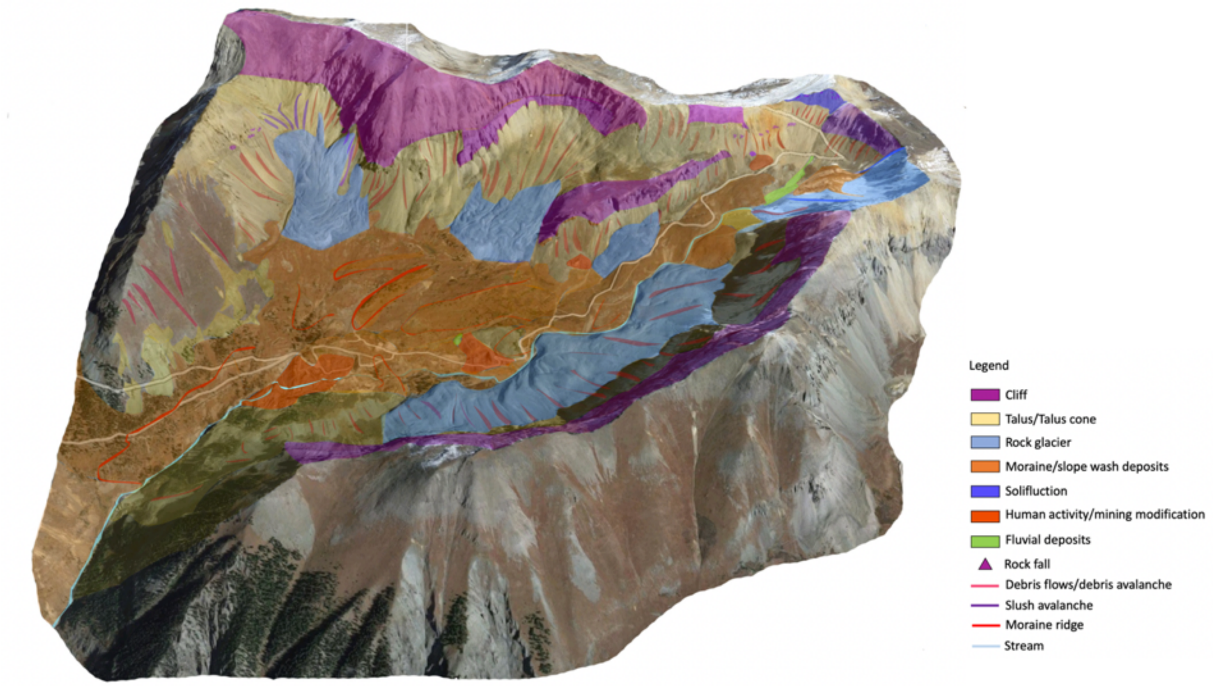

Figure 4.2. Landforms mapping for Savage Basin.

From the mapping, several types of mass movement are presented in the study area, which can transport sediment sources from a contributing zone to a down-slope sink. The major mass movement type in Savage Basin is debris flows. These debris flows transport sediment from several contributing landforms such as, talus, rockfalls or directly from cliffs, and then it can transport sediment to rock glaciers, talus in lower parts of the basin or to the deposition zone near fluvial channels. Slush avalanches are also presented in Savage Basin which create a slightly different sediment cascade compared to a debris flow. Slush avalanches override talus cones and in many locations transport debris to a rock glacier. Slush avalanches serve as minor sediment sources for rock glacier. The ridge below Imogene Pass has a large solifluction feature. Rock fall in Savage Basin occur beneath cliff faces and contribute sediment supply by supplying debris flows.

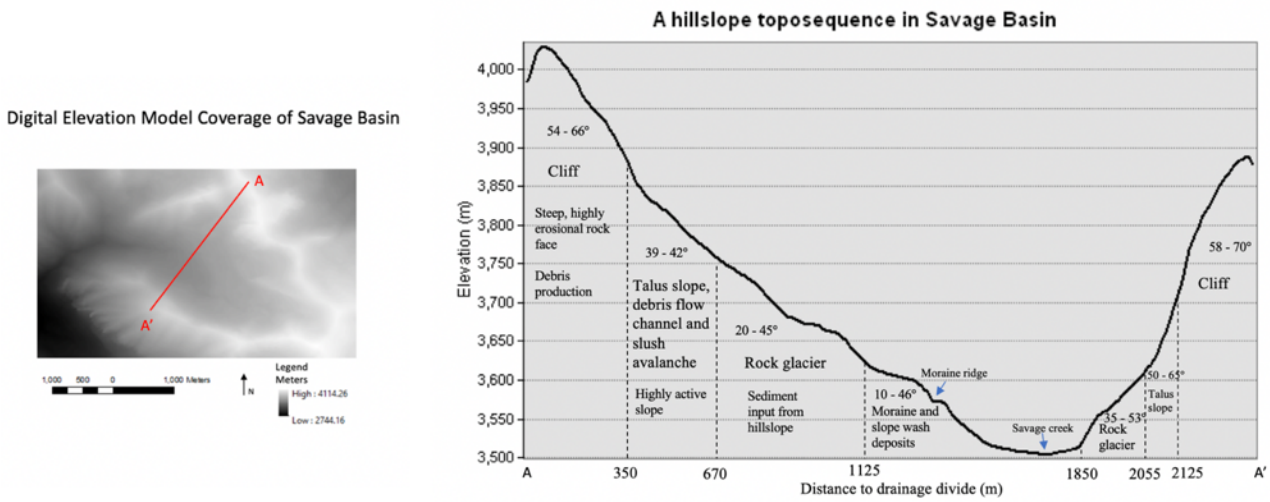

Figure 4.3. Hillslope toposequence in Savage Basin.

Table 4.1. Relative basin area of sediment storage and relative sediment cover (%).

Sediment storage landform types	Relative basin area (% whole basin)
Cliff	21.10%
Talus	33.50%
Talus cone	0.50%
Rock glaciers	17.80%
Fluvial deposits	0.30%
Moraine	25.10%
Human activity	1.70%

My geomorphic mapping shows a noticeable spatial distribution of sediment stores and cascades (figure 4.3 and table 4.1). The major deposits in Savage Basin are talus (33.5%). Cliff (21.2%), rock glaciers (17.8%) also account for major sediment storage landforms. Talus is formed mainly because debris flows can transport sediment from cliff or rock fall to talus slope.

Moraine deposits and fluvial deposits cover the floor of the basin and account for approximately 25.4 % basin surface.

The profile from the ridge to the stream channel displays steep gradients (70°) and a succession of various landform stores. Whereas the upper part of the basin is dominated by talus, the foot-slopes are buried by rock glaciers and moraine deposits. There are many examples of these stores being fed by debris flows and avalanches.

Potential sediment sources are mainly from cliffs, talus cones and rock falls. Most cliffs are in the higher parts of the basin where steep rock faces exist and generate rocks and sediment supply that can be transported to lower parts of the basin and serve as sources for sediment cascades. Various landforms have been identified as sediment storage or sinks such as talus, rock glaciers, moraines, and fluvial deposits. Moraines near Savage creek is a significant sediment storage sink in the valley floor of Savage Basin. If the storage landforms link other types of mass movement, then these sink landforms can also serve as a contributing zone and can provide sediment sources to other landforms. For example, talus or rock glaciers on hillslopes can temporarily store sediment from the cliffs or rock falls and then contribute sediment to the fluvial deposits near the stream channel. Slope wash deposits, moraines or fluvial deposits can be linked and transport materials to the stream channel. A detailed analysis is shown in the graph construction (figure 4.4 and figure 4.5).

Graph construction

A graph was constructed by using nodes and edges, with each node representing a landform that was mapped in Savage Basin, and each edge represents a sediment transport trajectory between any pair of nodes. Figure 4.4 shows the nodes and their links based on field mapping and aerial photo interpretation.

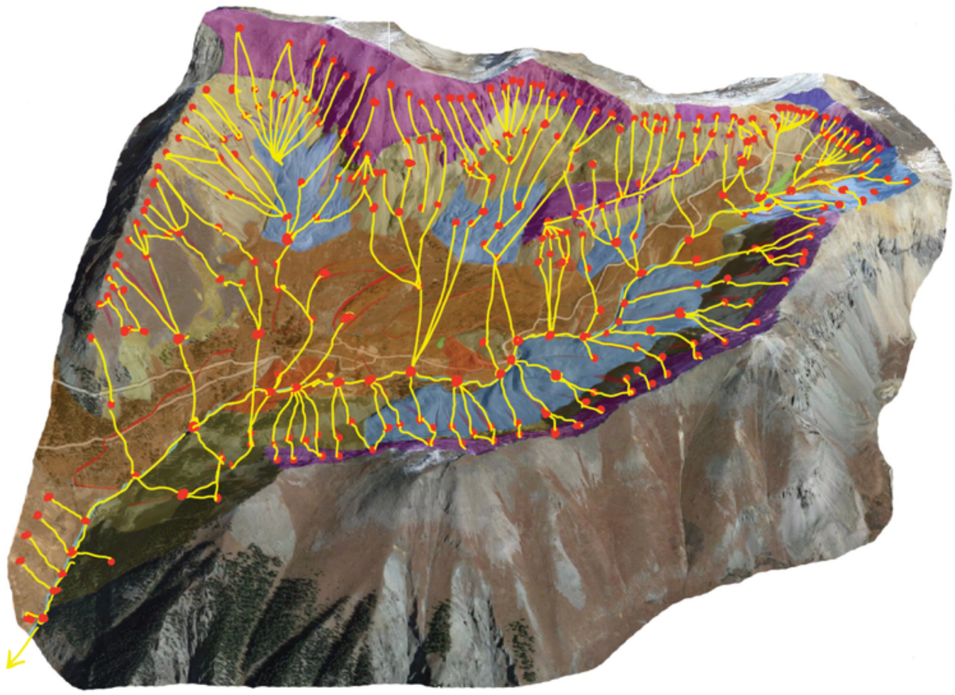

Figure 4.4. Nodes and links created for Savage Basin.

For visualization, the linkages between nodes were converted to straight lines in constructing the graph. Figure 4.5 shows the graph of sediment cascades in Savage Basin; the nodes represent landforms, and edges represent sediment pathways.

Figure 4.5. Graph of sediment cascades in Savage Basin.

Figure 4.5 provides a general view of a graph for sediment cascades and networks in the study area. Total nodes in this graph is 295, and the total edges is 303. Graph nodes and edges can be color coded by function and analyzed from different perspectives.

Graph nodes analysis

In a graph, a node can be identified as a source node, a link node or a sink node by its degree. The degree of a node is the number of edges that are incident or connected to it, the degree of a node is equal to the number of its neighbor nodes. In the Savage-Basin graph, a source node is the node that has 0 incoming edges, and its outgoing edges are > 0. A sink node is the node that has 0 outcoming edges and its incoming edges are > 0. A link node represents both its incoming and outgoing edges are > 0. A nodes graph is created based on the degree values (figure 4.6 and 4.7).

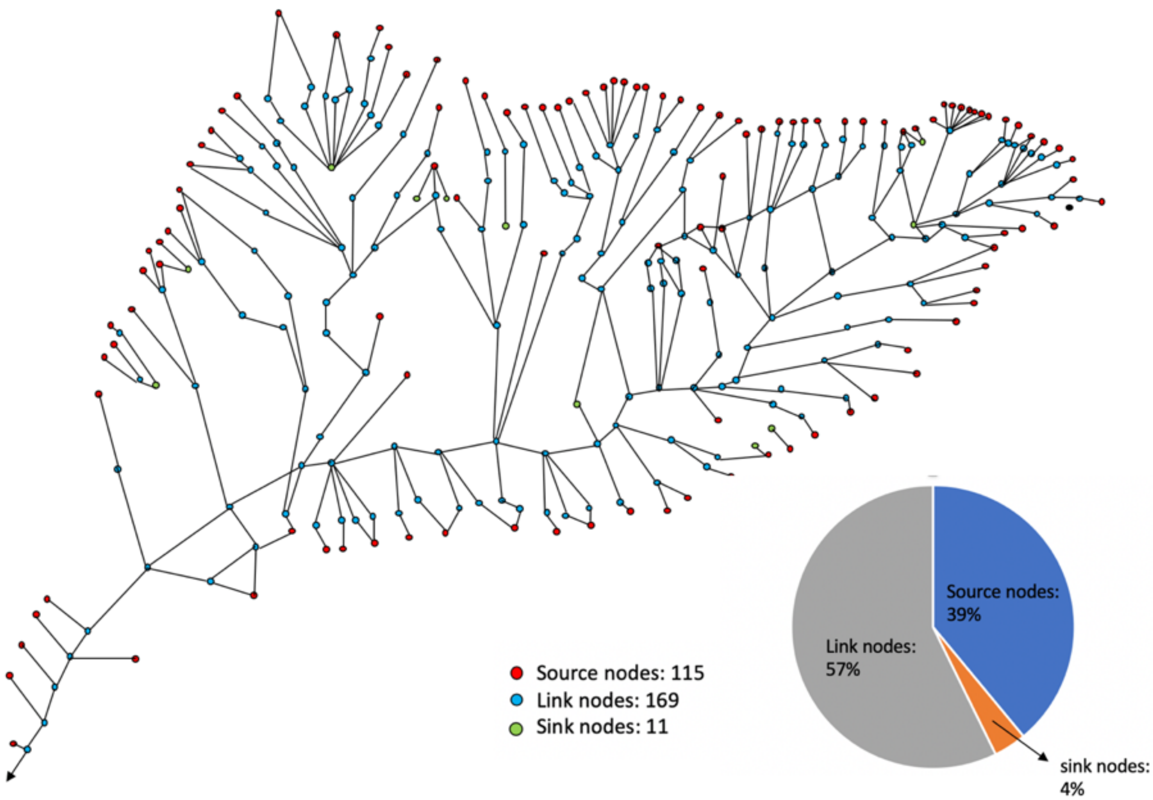

Figure 4.6. A graph with source, link and sink nodes and nodes statistics.

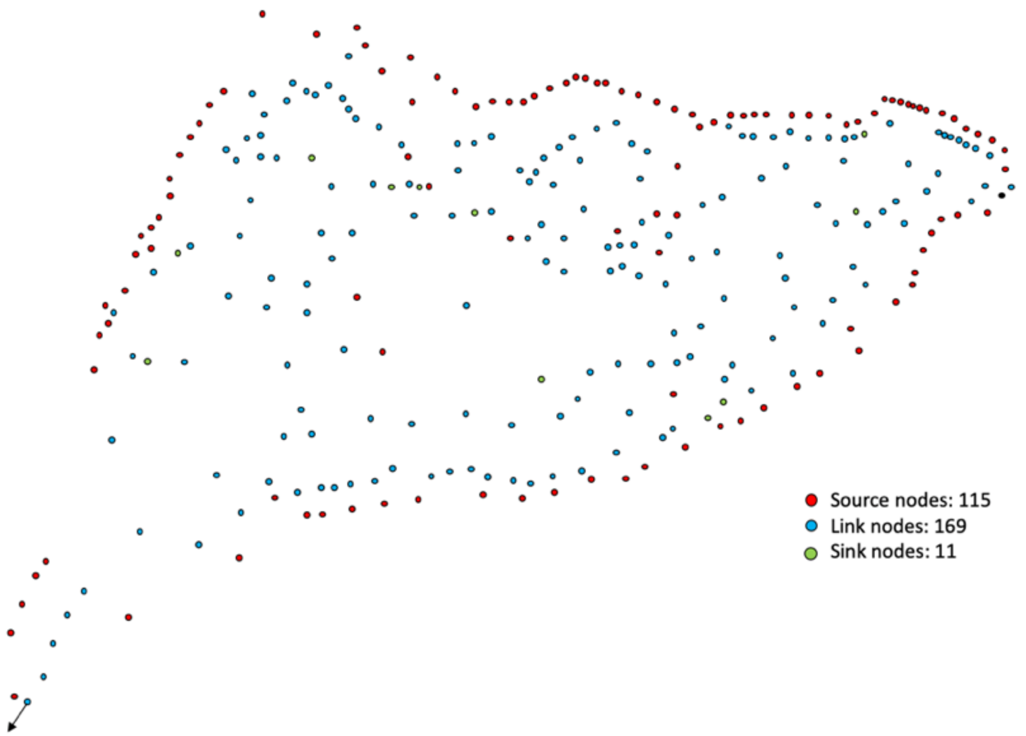

Figure 4.7 Graph of source, link and sink nodes without edges.

Study of Figures 4.6 and 4.7 shows source nodes and link nodes are dominant in Savage Basin, which suggests that in Savage Basin, most landforms serve as contributing zones or link functions for sediment cascades. Only 4% of the nodes are sink nodes. One would think that the number should be higher, the reason is that most moraines and slope wash deposits are not isolated, they are linked and transport sediment to a fluvial channel along the basin bottom in Savage Basin.

The overall nodes graph is dominated by source nodes near mountain ridge and link nodes on hillslopes. A second graph showing nodes with different types of landforms is shown in Figure 4.8.

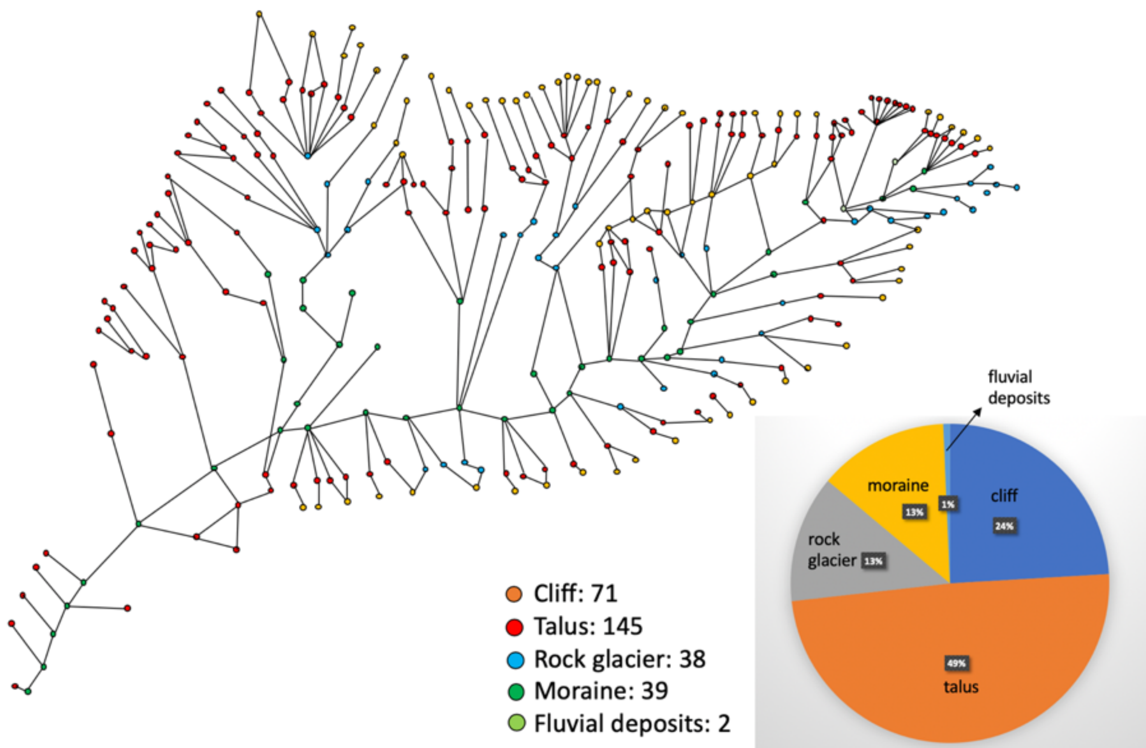

Figure 4.8. A sediment-cascades graph with nodes representing landform types.

In figure 4.8, talus and cliffs are dominant in Savage Basin. Analysis of the landform in Savage Basin suggests that only a very small portion of talus, rock glaciers and moraines are identified as sink nodes with no outgoing edge, which suggests that only a small portion of landforms accept sediment supply as a depositional zone. Most landforms nodes are either source nodes or link nodes in Savage Basin, these landforms either serve as contributing zones providing sediment supply or serve as linkages forming sediment cascades. This finding does suggest an interesting point that is not considered in graph theory – resident time and how to address it. This will not be addressed in my thesis, but it does make for an interesting future project.

An adjacency matrix (table 4.2) is created based on the graph in Figure 4.8. Mass movement has direction, thus, the graphs in this thesis are all direction graphs, and the matrix is created based on a directed graph, which means the matrix is asymmetric. In a square matrix, rows and columns are created that correspond to nodes in the graph, and element a_{ij} represents the number of edges between node i and node j. In this thesis each type of landform forms a node, and the value in the matrix is the number of edges linking any pair of nodes (*i.e.,* landforms).

The in-neighborhood size of a node is defined as the number of nodes from which a node can be reached. The out-neighborhood size of a node is defined as the number of nodes that can be reached by a specific node. For sediment cascades, the in-neighborhood nodes can be considered as a contribution zone (Heckmann and Schwanghart, 2013). Table 4.2 shows the value of each node's (*i.e.,* each landform) in-neighbor size and out-neighbor size, which reflects the degree of geomorphic coupling of any pair of landforms in Savage Basin.

Table 4.2. Landform matrix (based on graph in figure 4.8).

Landforms	Cliff	Talus	Rock glacier	Moraine	Fluvial deposits
Cliff	11	67	9	1	0
Talus	9	71	18	39	3
Rock glacier	-9	-18	18	19	2
Moraine	-1	-39	-19	34	1
Fluvial deposits	0	-3	-2	1	0

The column of each nodes shows the in-neighborhood size, and the row of each node shows the out-neighborhood size in Table 4.2. Negative numbers in Table 4.2 indicate mass movement processes cannot exist in that direction (*i.e.,* from a landform in first column to its corresponding landform in first row). From the matrix, one can see that talus has the largest in-neighborhood size compared to other landforms; the moraines have the largest out-neighborhood size of any landforms except cliffs. The cliff-to-talus node the largest out-neighborhood size.

Most landforms in Savage Basin receive talus from a contributing zone, and sediment in most landforms deposit at the floor of the basin as moraines. Cliffs contribute sediment supply directly, primarily to talus. Study of Figure 4.8 shows talus are primarily located between middle of hillslopes and the lower parts of the hillslope in Savage Basin. Moraines and slope wash deposits cover the floor of the basin, and the stream channel runs through the bottom of the basin.

Graph edges analysis

An edge in a graph represents a linkage between two nodes. In sediment transport, the edge represents a potential pathway of sediment transport. Figure 4.9 shows the potential pathways of sediment transport in Savage Basin, whereas the mass movement processes include rock falls, debris flows, slush avalanches, pathways from cliffs and pathways in rock glaciers, the slope wash and moraine deposits are pathways to the floodplain and stream channel. Total number of edges in the graph is 303; it is made up of 77 pathways from cliffs, 16 from rock falls, 121 from debris flows, 9 from avalanches, 18 pathways from rock glaciers, and 62 moraines or slope wash deposits transport pathways.

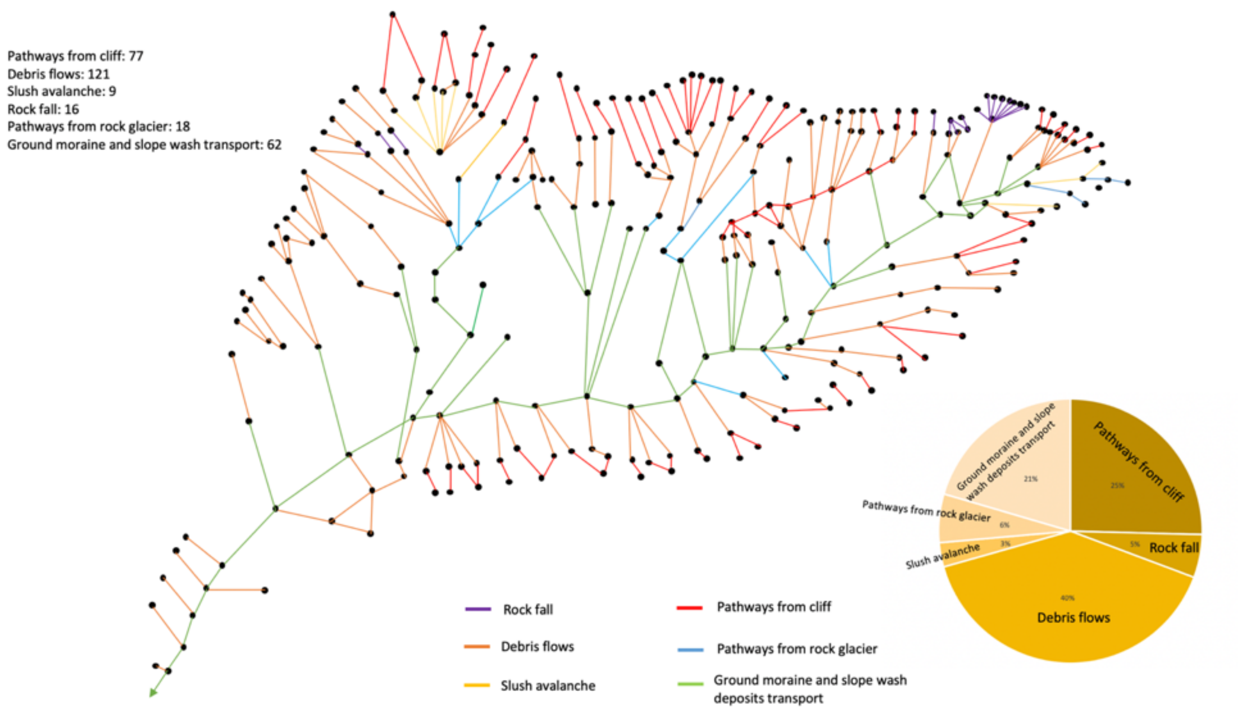

Figure 4.9. Map of graph for sediment cascades with edges in Savage Basin.

The graph (figure 4.9) is dominant by debris flows which transport sediment from cliffs/talus to adjacent landforms located on the side or floor of the basin, coupling between talus and other landforms. The most important mass movement transport processes in Savage Basin are debris flows, which form pathways from the cliffs.

Analysis of Figure 4.9 illustrates that moraines or slope wash deposition pathways are highly connected and can transport sediment from surrounding talus or rock glaciers to the stream channel. The reason why they are highly connected can be illustrated by analyzing a slope map of Savage Basin (figure 4.10).

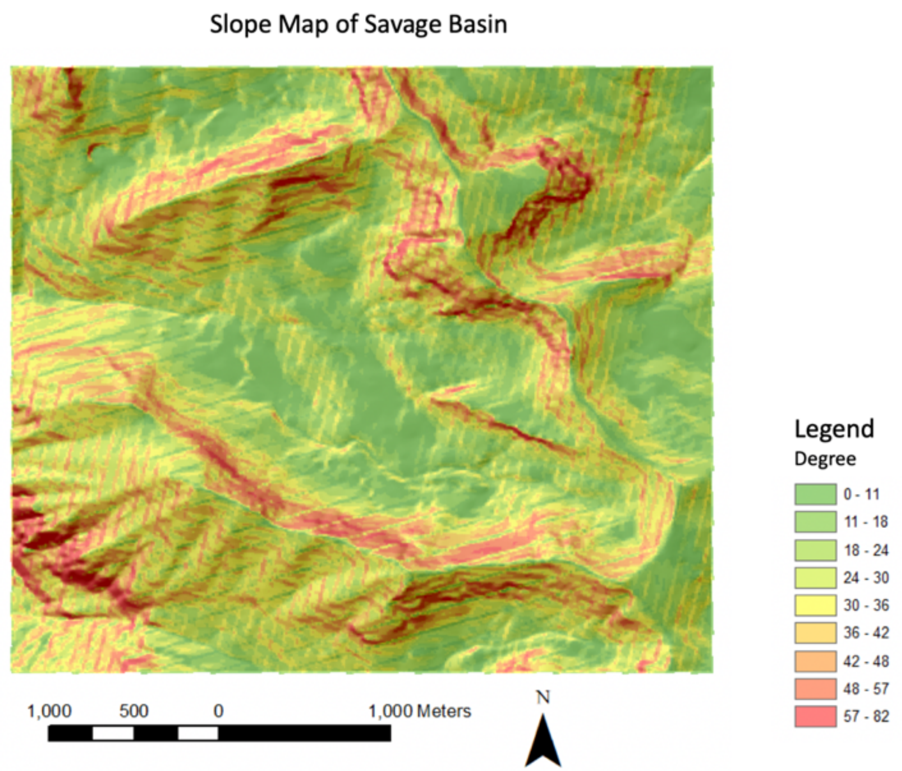

Figure 4.10. A slope map of Savage Basin.

Figures 4.9 and 4.10 show the basin floor along Savage Creek has a slope ranging from 30° to 57°, which is relatively steep. Thus, moraines and slope wash deposits on the bottom of Savage Basin are connected and serve as pathways to transport sediment into the stream all along its channel.

Sediment cascades interpretation in graph

The transfer of sediment across a landscape, along a sequence of landforms, and effected by different geomorphic processes, has been addressed using concepts of sediment cascades (Burt and Allison, 2010). Conceiving landscape compartments linked by sediment fluxes as a network is intuitive.

Connectivity is a driver of hydrological and geomorphic processes within a catchment and an emergent property of the latter (Slaymaker, 2006) that is caused by these processes and their interaction. As a system property, it results from hydrological and geomorphic coupling between the components of the system (Faulkner, 2008, Heckmann and Schwaghart, 2013). Hence, setting up a network model of coupled landforms enables investigation of both local coupling relationships and the structure of the whole catchment.

For sediment cascades discussed in this thesis, edges in a graph represent the two linked nodes (*i.e.,* landforms) are coupled. When considering sediment cascades, edges in the cascades graph are equal to paths – that is, the sequence of edges which link the nodes in this cascade trajectory. A Path length is equal to the numbers of edges this path contains. According to Hooke (2003), connectivity is the potential for a specific particle to move through the system. Thus, the paths in the cascade graph begin at a source node and ends at a storage node. Pathways in the depositional zone of Savage Basin are all highly connected. The paths in the sediment cascades graph begin from a source node and end at the node that represents moraines, slope wash deposits, or fluvial deposits along that path.

Figure 4.11 shows sediment cascades in Savage Basin. Again, most sediment sources are provided by cliffs at mountain ridges surrounding the basin and by rock fall onto hillslopes, which serve as source zones. Almost all cascades in Savage Basin eventually end on the floor of the basin or into the stream channel; the floor of the basin and stream channel serve as sink zone. Sediment cascades transport processes shown in the graph include six types as shown in Figure 4.11.

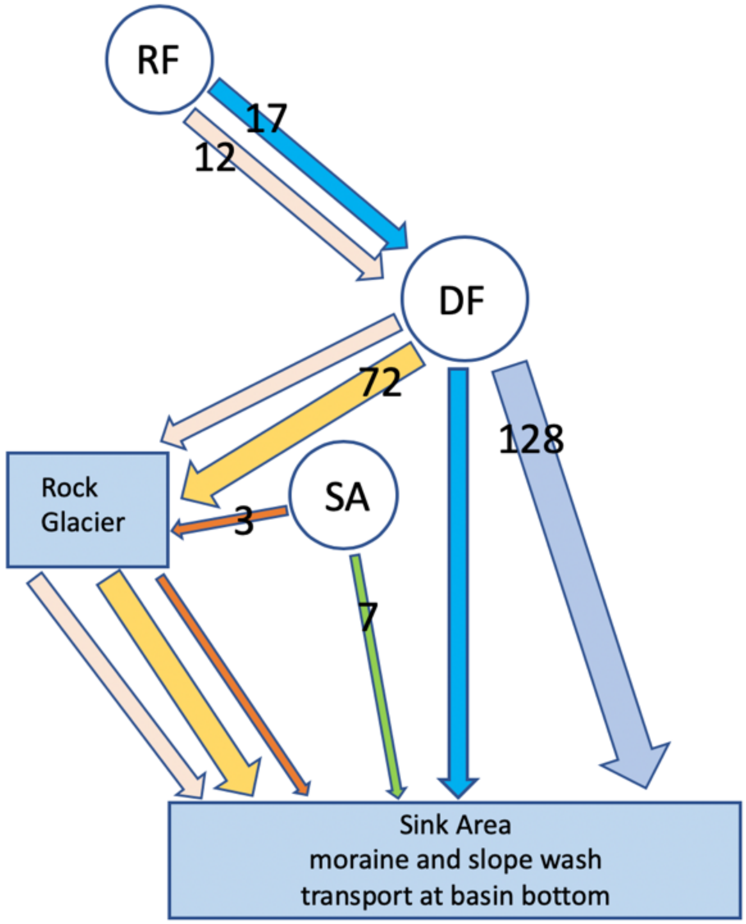

Figure 4.11. Summary graph of sediment cascades in Savage Basin. RF represents rock falls, DF represents debris flows, and SA represents slush avalanches.

The numbers in figure 4.11 represent edges weight, which equal to the total number of edges in a sediment cascade. The dominant cascades processes are debris flows, which directly link to the sink zone, making up 53% of all cascades. Most cascades are single-process paths in Savage Basin. The 13% cascade processes include two-processes paths as shown in Figure 4.11.

The ways landforms are coupled effect the transfer of sediment from sources to the outlets. According to Hooke (2003) and Heckmann and Schwanghart (2013), a higher connectivity in sediment cascades means more possible pathways linking sediment source to sink. So, if sediment pathways can be directly connected from source to sink with one mass movement type, it has a low connectivity, but a more effective geomorphic coupling. Thus, most sediment cascades in Savage Basin have high geomorphic coupling efficiency and low connectivity. This fact is very important when one considers the risks associated with slope stability in Savage Basin.

Analysis of major mass movement complexes

Landscape can be defined as the physical coupling of landforms. Changes in the coupling of system components (*i.e.,* changes in connectivity) lead to changes in morphodynamics and sediment budgets that are largely independent of external forcing (Wainwright, 2006).

The graph (figure 4.9) shows a cascading network for Savage-Basin landscape. Five major mass movement complexes present in Savage Basin are shown in Figure 4.12.

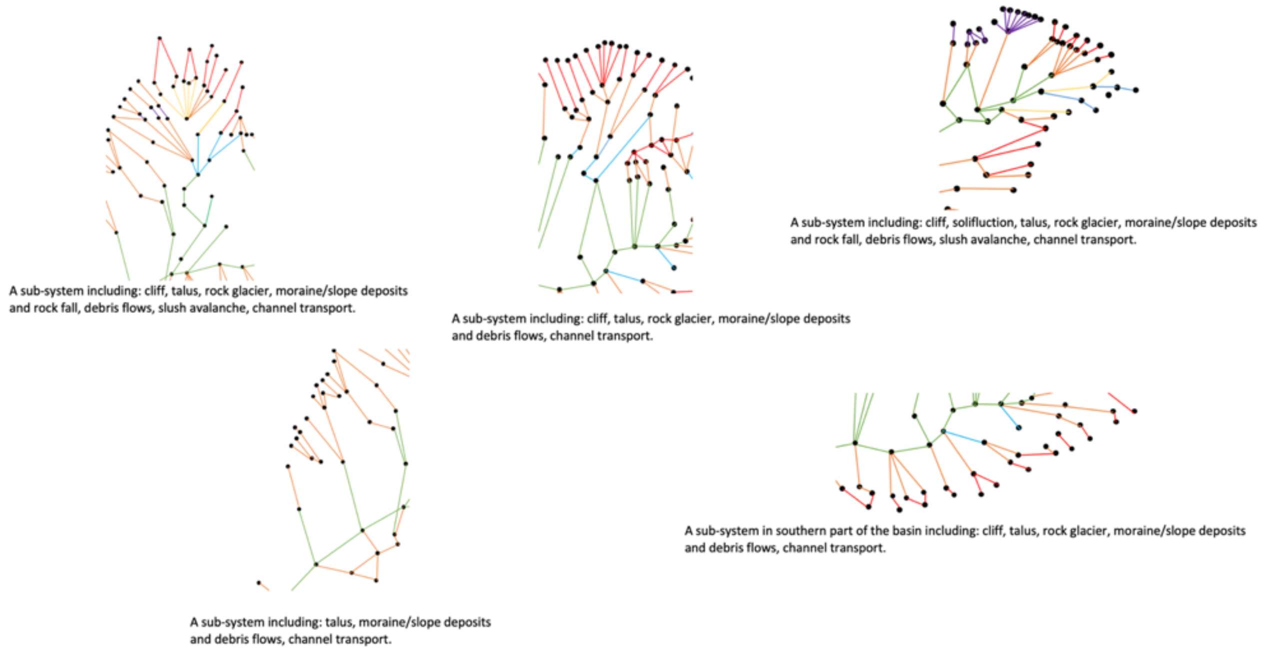

Figure 4.12. Major sub-graphs of Savage Basin cascades.

The five mass movement complexes are shown in Figure 4.12, different landforms and different sediment cascades show the specific transport processes.

The first mass-movement complex (figure 4.13), a rockfall complex, shows that cliffs, rock glaciers and rock falls are sediment sources in the contributing zone. Talus deposits also provide sediment supply for debris flows and slush avalanches. Analysis of the surficial deposits map (figure 3.7) shows that the major deposits are talus, rock-glacier deposits and glacial drift. Debris flows in this complex have high geomorphic coupling. Three types of mass movements, which are debris flows, solifluction and slush avalanches, move sediment from the mountain ridge in southeastern part of Savage Basin to the basin floor. This complex reflects a high connectivity compared to other complexes.

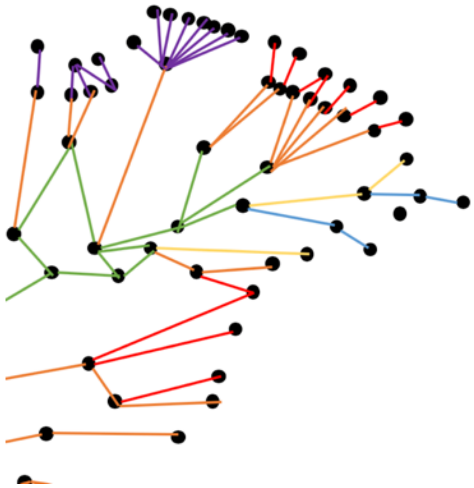

Figure 4.13. Rock fall complex in Savage Basin.

A second sediment transport complex (figure 4.14), rock glacier I complex, shows that debris flows transport sediment from cliffs to rock glaciers and the basin floor. This complex contains a large amount of talus, which has a high geomorphic coupling in the northern part of the basin.

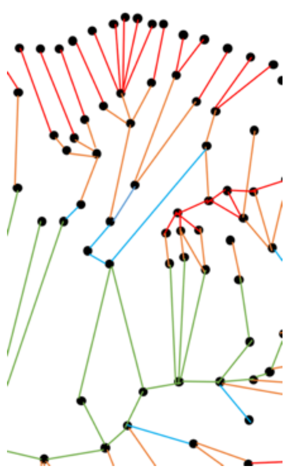

Figure 4.14. Rock glacier complex I in Savage Basin.

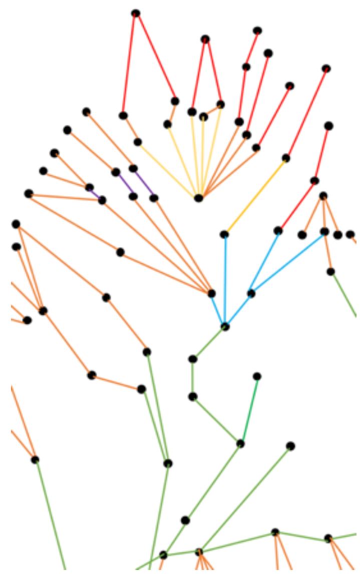

Figure 4.15. Rock glacier II complex in Savage Basin.

The third sediment transport complex (figure 4.15), rock glacier II complex, shows that both debris flows and slush avalanches transport sediment from cliffs to rock glaciers and the basin floor with high coupling degrees. This complex also contains rock falls, and a large amount of talus serves as a sediment source for mass movement.

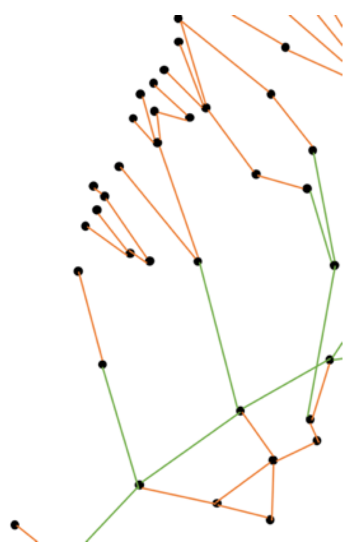

Figure 4.16. Talus complex in Savage Basin.

The forth sediment transport complex (figure 4.16), the talus complex, shows that only debris flows transport sediment from talus to basin floor. This complex's landforms contain only talus, and the talus serves as a sediment source for debris flows without a steep cliff face near the basin ridge. This complex is located in the western part of Savage Basin.

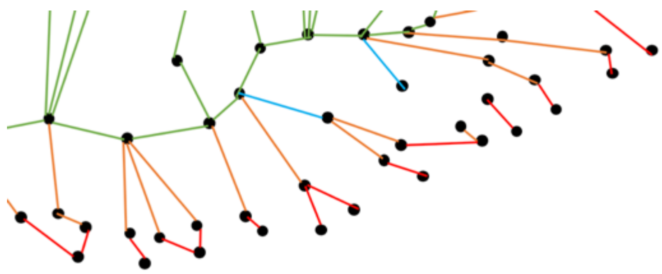

Figure 4.17. Southern part complex in Savage Basin.

Compared to the mass movement in northern part, the sediment cascades in the southern part (figure 4.17) of Savage Basin have relative low connectivity without many possible pathways. Mass movement types in this complex are mainly debris flows, which transport sediment from cliffs and talus to rock glaciers and the basin floor along the stream channel.

These five major sediment cascades are typical and prevalent in Savage Basin. In northern part, the basin sediment cascade has a high geomorphic coupling. The sediment sources here are mainly cliffs and talus. The connectivity of Savage Basin in the eastern part is higher than that in other cascades systems. In the southern part of the basin, connectivity is relatively low, and only one type of sediment-cascades transport processes is dominant, which is sediment transported by debris flows from talus or cliffs to rock glaciers and the basin floor.

Chi square analysis

The Chi-Squared test statistic was created to test for normal distribution in data analysis. The basic idea behind the use of the Chi Squared test is to evaluate if significant differences exist between expected frequencies of an objective being studied in several categories (Fisher, 1922).

It is important to determine that the distribution of landforms I am examining in Savage Basin are not independent. To check the distribution of landforms in Savage Basin, their normality, and the spatial extent on my data, I used the Chi-Squared statistic. To calculate chi square (χ^2), the following equation is used.

$$\chi^2 = \sum \frac{(o-e)^2}{e}$$

where o represents observed nodes for each type of landforms, and e represents expected nodes for each type of landforms.

There are 295 nodes represented on the graph. These nodes represent five different landforms types: cliffs, talus, rock glaciers, moraines, and fluvial deposits.

Testing distribution of landforms

For this Chi-Square test, the null hypothesis (H_0) states that the five types of landforms in Savage Basin are distributed in the basin evenly. The total number of nodes can be averaged to determine the expected nodes for each type of landform. The degrees of freedom are equal to total number of landform types less one. The Chi-Square result is shown in Table 4.3.

Table 4.3. Distribution of landforms chi square test.

Landforms	cliffs	talus	rock glaciers	moraines	fluvial deposits	total	
Observed nodes (o)	71	145	38	39	2	295	
Expected nodes (Mean) (e)	59	59	59	59	59	295	
						Chi square	DF
(o-e)^2/e	2.44	125.36	7.47	6.78	55.07	197.12	4

Table 4.3 shows that the calculated Chi-square value is 197.12, which is very large; thus the null hypothesis that the five different types of landforms are distributed evenly in Savage Basin is rejected. The five types of landforms in Savage Basin are not distributed evenly.

Testing normality of landforms

In this Chi-Squared test, the null hypothesis (H_0) states that the five types of landforms are normally distributed in Savage Basin. The expected nodes for this test are calculated by using the area under a standard normal curve to the left of z given in the z tables. To calculate a z value, the following equation is used.

$$z = \frac{Observed\ nodes\ - m}{s}$$

where m is mean of total nodes, and s is nodes of standard deviation. The degrees of freedom are equal to total number of landform types less three. The Chi-Square result is shown in Table 4.4.

Table 4.4. Landform normality chi square test.

Landforms	cliffs	talus	rock glaciers	moraines	fluvial deposits	total	s
Observed nodes (o)	71	145	38	39	2	295	53.92
z value	0.22	1.59	-0.39	-0.37	-1.05		
Area under standard normal curve (a)	0.59	0.94	0.35	0.36	0.14		
Expected nodes (a*295) (e)	173	279	103	105	43		
						Chi square	DF
(o-e)^2/e	60.3	64	40.8	41.43	38.75	245.28	2

Table 4.4 shows that the calculated chi square is 245.28, which is very large, so the null hypothesis, which states that the five types of landforms are normally distributed in Savage Basin is rejected. The five types of landforms are not normally distributed in Savage Basin.

Testing spatial extent of landforms

In this use of the Chi-Squared test, the null hypothesis (H_0) states that the nodes representing the five types of landforms correspond to the relative area of the five types of landforms in Savage Basin. The relative area for each type of landform serves as expected nodes in this test. The Chi-Square result is shown in Table 4.5.

Table 4.5. Landform spatial extent chi square test.

Landforms	cliffs	talus	rock glaciers	moraines	fluvial deposits	total
Observed nodes (o)	71/295	145/295	38/295	39/295	2/295	1
Expected nodes (relative area) (e)	21.10%	34.00%	17.80%	26.80%	0.30%	100.00%
						Chi square
(o-e)^2/e	0.004	0.068	0.014	0.069	0.005	0.159

In table 4.5, the Chi-Square number (0.159) is very small. The null hypothesis cannot be rejected. These nodes representing the five landform types in the graph correspond to the landforms relative area of the basin. There is no significance difference between the observed nodes and the expected nodes. It illustrates that the nodes I constructed in the graph are reasonable and reliable.

The Chi-Squared tests results suggest that landforms in Savage Basin are not distributed evenly. The five types of landforms are not normally distributed in the basin. By applying the Chi-Squared test, the nodes in the graph are compared with the relative area for each type of landform, and it shows that the nodes for each type of landform represented in the graph have no significance difference from the relative areas of each landform in the basin. Thus, the graph constructed in this thesis research is reliable.

Explanation of landscape evolution for Savage Basin

Processes operating from the Pleistocene to the present are responded for the current look of Savage Basin. Graph theory was used to identify the various sediment cascades and to help construct a dynamic understanding of how the present Savage Basin evolved. Based on field work, aerial photo interpretation, geologic map, and various published work (Blair *et al.,* 1996, Blair and Bracksieck, 2011), the following explanation of the evolution of Savage Basin is produced.

Following uplift of the San Juan Mountains and deposition of extensive volcanic deposits, the region entered a period of marked climatic change, which resulted in glaciation of the area (Guido *et al.,* 2007).

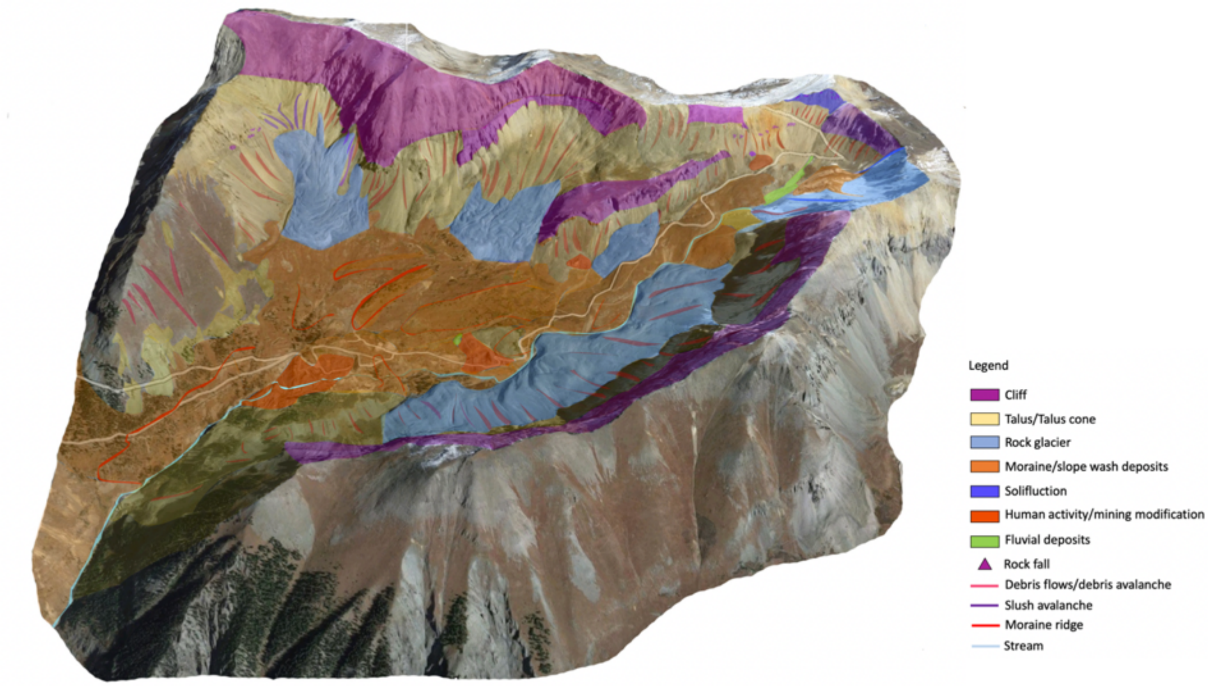

Figure 4.18. landforms mapping for Savage Basin.

Savage Basin (figure 4.18) was severely glaciated and is an alpine cirque. The glaciers that formed in this cirque extended the length of the basin. Several recessional moraines were deposited. Although lateral moraines were probably deposited along the valley side, no deposit are currently present.

Following the glaciation, the basin has been dominated by mass movement. Freeze-thaw activity following glaciation produced an abundant of talus. The talus accumulated along slope at the basin of cliffs.

Periglacial condition transitioned from full glacial to Holocene environment. During this time parts of the glaciers were covered with debris and formed ice-cored rock glaciers.

Today much of the basin is draped with mass-movement deposits. These deposits are talus cones, rock glaciers, avalanche deposits, slush avalanche deposits, and debris cones.

Savage Creek extended from near the head of the basin in the upper cirque to its exit from the basin. A small floodplain is adjacent to the stream towards the end of the basin. The basin has experienced a small amount of fluvial erosion.

The upper part of the basin experienced minor glaciation during the little Ice Age. A small terminal moraine is still present just beyond the cirque floor.

The present-day landscape has been altered by extensive human activity in the lower part of the basin where a milling operation occurred during the late 1800's and 1900's.

Theoretical framework applied in other areas

The simulation graph and analysis methodology for graph nodes and edges can be applied in other alpine basins (figure 4.19) in San Juan Mountains.

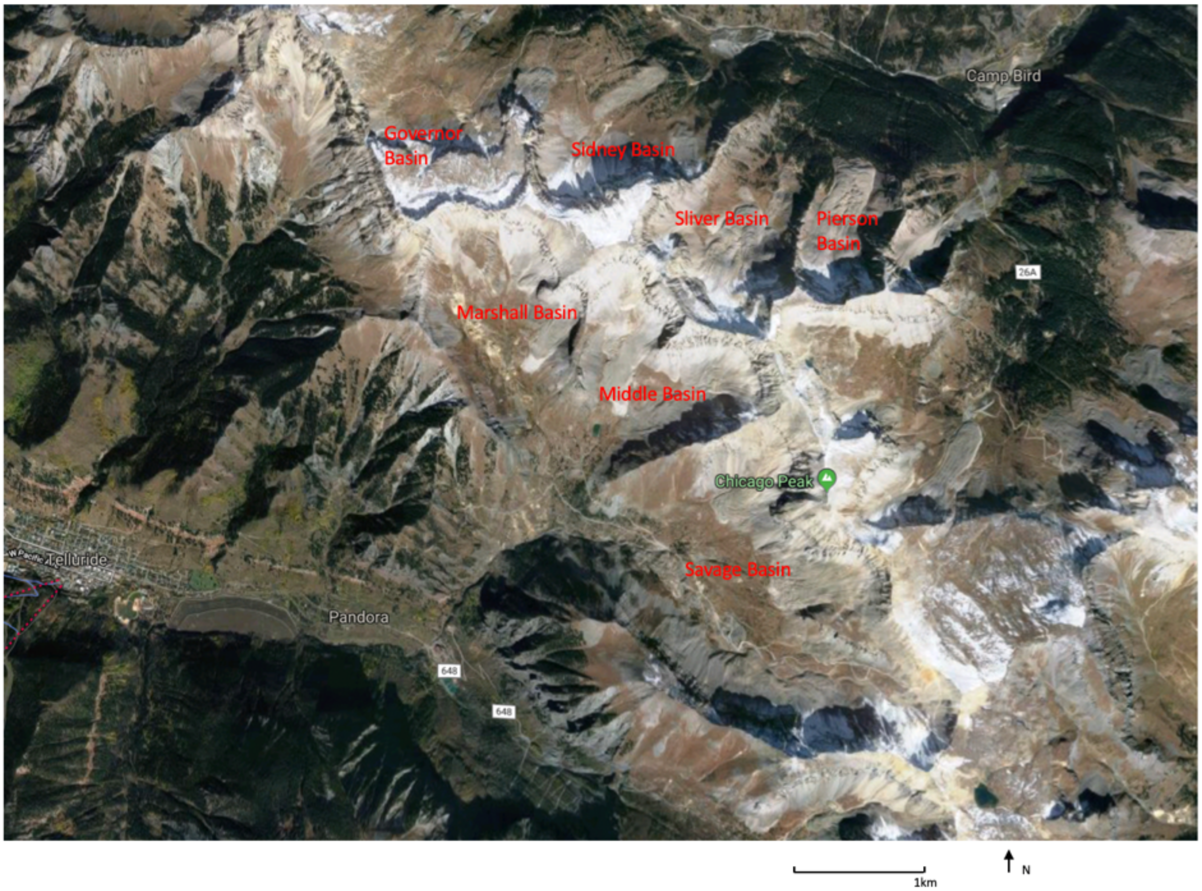

Figure 4.19. Different alpine basins in the San Juan Mountains.

Figure 4.19 shows different alpine basins near Savage Basin, such as Middle Basin, Marshall Basin, Sliver Basin, Pierson Basin, Sidney Basin, and Governor Basin. Graph theory methodology produced by this thesis research for Savage Basin can also be used to analyze sediment cascades processes and landscape evolution for the alpine basins shown in the Figure 4.19.

The graph theory methodology in this thesis provides a general theoretical framework for basins in alpine environment.

CHAPTER V

CONCLUSIONS

Summary

This thesis research applied graph theory to construct a simulation model for sediment cascades in the Savage Basin. Different landforms and transport processes were modeled by nodes and edges, respectively. The modeled edges are used to construct a summary of the sediment-cascades graph to analyze geomorphic connectivity in the study area.

Mass movement in alpine basins in the San Juan Mountains plays a major role in landscape evolution of the various basins. The linkage of distinct landforms or landscape units by sediment transport is referred to as geomorphic coupling (Harvey, 2001).

Unfortunately, no one has examined the cascade of debris from the ridges, surrounding these basins, to the stores, which are the various landform, to the stream channel, and out of the basin. I have studied the cascade of debris in Savage Basin.

The first objective, which is identifying various sediment sources, pathways and processes, was fulfilled by mapping landforms on a 3-D terrain model image.

The second objective, which is using graph theory to identify nodes and linkages, was fulfilled by creating a simulation graph, nodes and edges in the graph are analyzed respectively.

The third objective, which is explaining landscape evolution of the Savage Basin, was fulfilled by analyzing sediment cascades and geomorphic history of Savage Basin.

Most landforms can be considered as serving as contributing zones or intermediate zones in which they become sediment storage areas as well as provide sediment supply for other sinks. Sediment-source zones are dominant the mountain ridge surrounding Savage Basin. Along the floor of the basin. Moraines and slope-wash deposits are highly connected at the bottom of the basin, and sediment can be transported from these to stream channel and out of the Savage Basin.

In the contributing zones, talus, which is very extensive along the hillslopes in the basin, provides most of the sediment supply to other landforms. Moraines serve as a depositional zone for sediment transported from surrounding landforms.

Debris flows are the dominant mass movement processes in Savage Basin. Debris flows couple cliffs, talus, rock glaciers, and basin bottom landforms. The major mass movement transport processes for Savage Basin are debris flows and sediment pathways from the upper cliffs. Most sediment cascades in Savage Basin have high geomorphic coupling efficiency and low connectivity.

Most sediment sources are fed by materials from cliffs at the basin ridge and rock falls along the hillslope, which serve as source zones. Almost all cascades in Savage Basin eventually end along the floor of the basin and contribute to the stream channel, which serves as a sink zone. Most cascades are single-process paths in Savage Basin, which suggests a high efficiency of geomorphic coupling and low connectivity are prevalent in Savage Basin.

Five major sediment transport processes at various locations in the basin explain landscape evolution in Savage Basin. Landscape evolution of Savage Basin is explained by analyzing the geomorphic history, landforms mapping, and characteristics of sediment cascades in the basin.

Conclusions

Glaciation, mass movement, and fluvial play important roles in understating landscape evolution in the San Juan Mountains. By constructing a simulation model using graph theory, the characteristics of sediment transport processes in an alpine basin can be explained in a quantitative way.

Graph theory is a useful tool to view transport processes in an alpine basin. It can provide a clear data matrix for network analysis, as well as the connectivity between various components. Various properties and dynamics of alpine cascading system can be identified and explained by utilizing graph theory.

Future study of sediment transport processes in Savage Basin could be accomplished by one creating a numerical transport model based on data from a digital elevation model, in which raster cells with different attributes can represent nodes in a graph, and edges between nodes can be constructed using different algorithms. This future research can provide a more detailed and precise matrix for nodes and edges data, contributing zone, deposition zone, and cascade connectivity of a dynamic sediment cascade system.

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